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DEVELOPMENT OF CRITERIA FOR MONITORING OF AIRPORT GROUND POLLUT--ETC(U)

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**DEVELOPMENT OF CRITERIA
FOR MONITORING OF
AIRPORT GROUND POLLUTION**

Volume II - Data Validation Procedures

Science Applications, Inc.
1200 Prospect Street
La Jolla, California 92038



November 1978

FINAL REPORT



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Prepared for

**U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590**

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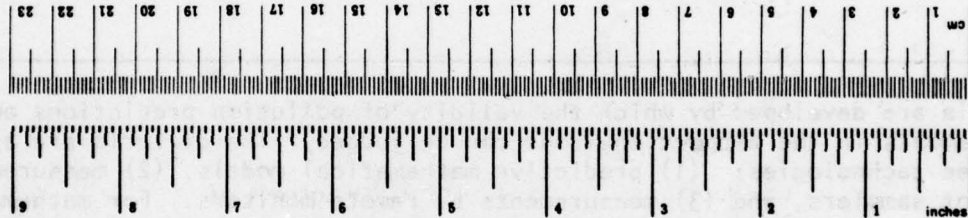
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16. Abstract Criteria are developed by which the validity of pollution predictions and measurements in the airport environs can be judged. The criteria are applied to three technologies: (1) predictive mathematical models, (2) measurements by point samplers, and (3) measurements by remote monitors. For mathematical models the criterion is the agreement between predicted and measured pollution levels. Various mathematical models are described, analyzed and ranked by weighted attributes as screening models and as validation models. For point samplers, the criteria have been developed based on EPA-approved measurement principles and procedures for testing performance characteristics and for determining a consistent relationship to reference methods. Remote monitors belong to an evolving technology that has not yet been approved as to measurement principles. Thus criteria are developed to select certain remote sensing systems as potential candidates for air enforcement monitors. Data validation procedures are developed for the selected remote monitors.		
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
acres	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
teaspoons	teaspoons	5	milliliters	ml
tablespoons	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cup	0.24	liters	l
pt	pint	0.47	liters	l
qt	quart	0.95	liters	l
gal	gallon	3.8	liters	l
cu ft	cubic feet	0.03	cubic meters	m ³
cu yd	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	1.1	yards	yd
		0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	acres
MASS (weight)				
g	grams	0.035	oz	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	short tons
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
m ³	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



*1 in. = 2.54 (exact). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10-286.

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7.0 DATA VALIDATION PROCEDURES

The procedures formulated in this Section constitute the criteria that will allow the FAA to methodically interrogate remote monitored data, taken for R&D and future air enforcement purposes. There are general procedures that apply to all systems. These are described first. Then there are special procedures applying to those individual remote monitor systems that were selected to be potentially useful in Section 6.2.2 for the R&D and future air enforcement applications.

7.1 Procedures Applicable to All Remote Monitors

There is a basic differentiation between R&D application and air enforcement application. For R&D, the monitor does not have to be designated as an "equivalent method", but must fulfill some specified performance requirements, while for air enforcement the monitor must only be designed as an "equivalent method".

The basic interrogation or data validation procedures can be phrased in the form of five questions:

1. Has the remote monitor that is collecting data in the vicinity of an airport been selected according to the selection criteria outlined in Section 6.0? There exist two major differences in the two applications: For R&D monitoring, the remote data do not need to be relatable to the standards, and eye safety limits can be relaxed, while for air enforcement monitoring, the remote data must be relatable to the standards and eye safety regulations must be observed.
2. What is the theoretical performance of the remote monitor? This can be answered by a step-by-step calculation of the signal-to-noise ratio, assuming known or optimum, e.g., detector-noise-limited, parameters. For R&D

application, the results of the calculation will indicate whether or not the instrument is sensitive enough in the concentration and distance range for the intended measurement.

3. Has the instrument fulfilled the equivalency requirement?

This question is relevant only for the future air enforcement application. If present procedures are followed, only data taken by individual instruments designated by manufacturer, model number. etc. and approved by the EPA and notice of acceptance duly published in the Federal Register need be accepted.

4. Have field calibrations been performed? For R&D

application, established experimental practices of calibrating should be followed, namely as often as deemed necessary. For future air enforcement application, calibration before and after data collection is required.

5. Is the operator(s) of the remote monitor competent?

The complexity of the remote monitors make it mandatory that the operator must be competent and familiar with the instrument, since it will be nearly impossible to make these complex machines "foolproof".

A logic diagram for a basic interrogation or data validation procedure is shown in Figure 7-1. It indicates the differentiation between air enforcement and R&D application. While the interrogation in the case of air enforcement appears more straightforward than for R&D, it is more demanding because of the requirement for demonstrating equivalency. The interrogation in the case of R&D application is more flexible, allowing even the use of a non-selected method. Nader et al. (229)

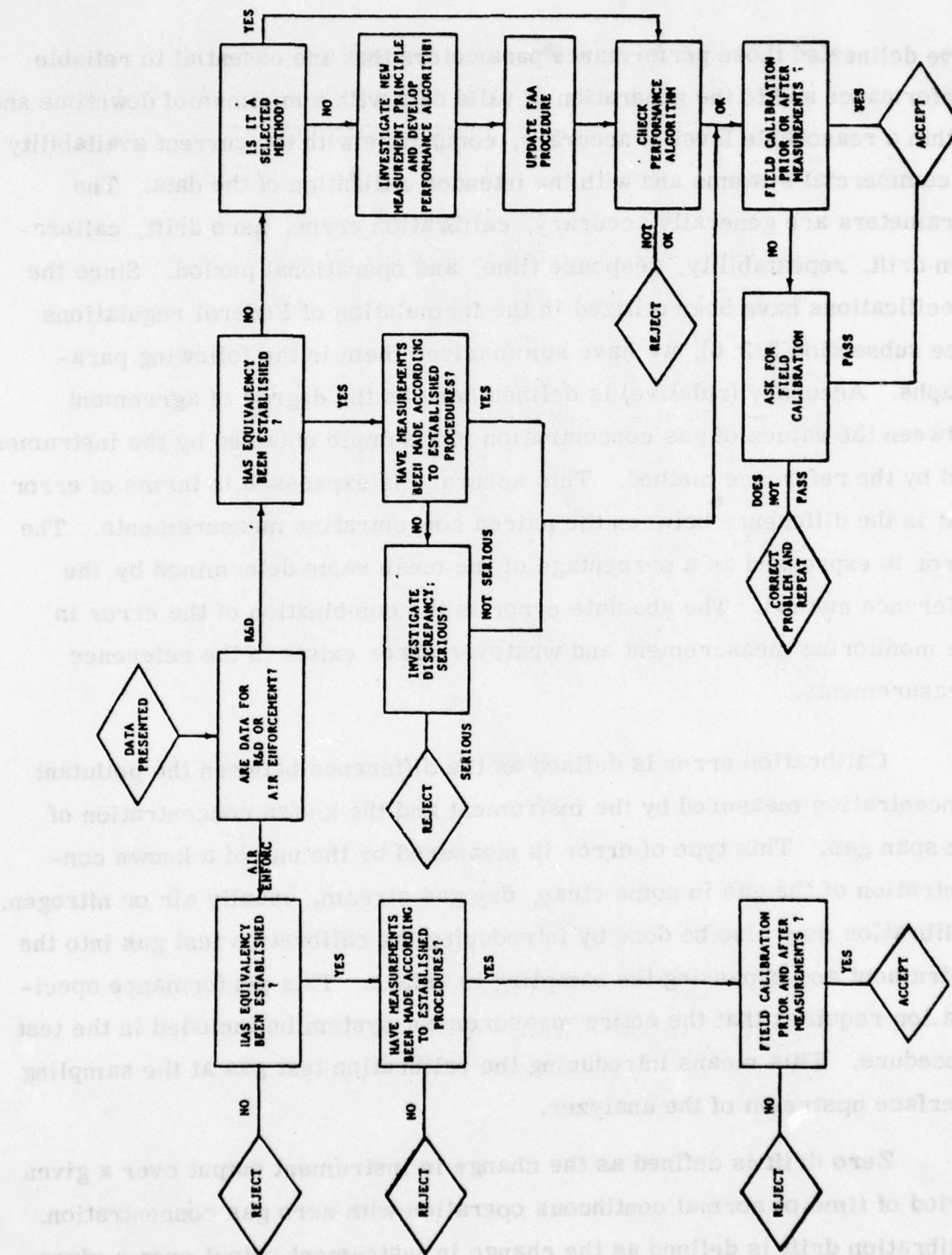


Figure 7-1. Data Interrogation and Validation.

have delineated those performance parameters that are essential to reliable performance and to the generation of valid data with a minimum of downtime and within a reasonable level of accuracy, compatible with the current availability of commercial systems and with the intended utilization of the data. The parameters are generally accuracy, calibration error, zero drift, calibration drift, repeatability, response time, and operational period. Since the specifications have been utilized in the formulation of Federal regulations (see subsection 3.2.6), we have summarized them in the following paragraphs. Accuracy (relative) is defined here as the degree of agreement between the values of gas concentration of a sample obtained by the instrument and by the reference method. This accuracy is expressed in terms of error that is the difference between the paired concentration measurements. The error is expressed as a percentage of the mean value determined by the reference method. The absolute error is the combination of the error in the monitoring measurement and whatever error exists in the reference measurements.

Calibration error is defined as the difference between the pollutant concentration measured by the instrument and the known concentration of the span gas. This type of error is measured by the use of a known concentration of the gas in some clean, dry gas stream, usually air or nitrogen. Calibration may also be done by introducing the calibration test gas into the instrument and bypassing the sampling interface. This performance specification requires that the entire measurement system be included in the test procedure. This means introducing the calibration test gas at the sampling interface upstream of the analyzer.

Zero drift is defined as the change in instrument output over a given period of time of normal continuous operation with zero gas concentration. Calibration drift is defined as the change in instrument output over a given

period of time of normal continuous operation when the gas concentration remains the same. Zero and calibration drift are critical parameters that have a direct effect on calibration error and ultimately on the accuracy of the data output.

Repeatability is defined as a measure of the measurement system's ability to give the same output reading(s) upon repeated measurements of the same pollutant concentration(s).

Response time is defined as the time interval from a step change in pollutant concentration at the input to the measurement system to the time at which 95 percent of the corresponding final value is reached. The response time of a measurement system is strongly influenced by the sampling approach used.

The operational period is a minimum period of time over which a measurement system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

Although Nader et al. have specifically developed the performance specifications for stationary-source monitoring systems, they are applicable, in general, to other types of sampling situations. Thus we find that the conclusions reached by Dieck and Elwood⁽²³⁸⁾ about emission analysis of gas turbine engines are supportive of the specifications as developed by Nader et al. Since Dieck and Elwood's conclusions are based on practical experience, we believe it is important to quote them verbatim.

"Without a knowledge of the measurement accuracy, the significance of observed differences cannot be assessed. In addition, the average emission level that a group of engines must achieve for compliance is a function of the accuracy of the measurement of the exhaust constituents; i. e., the less accurate the measurement, the lower the average level must be to assure that essentially all engines pass the compliance tests. The accuracy assessment specifically

included: 1) test instrument precision, 2) calibration gas accuracy and 3) sample error due to the distribution of data resulting from gas concentrations that are spatially non-uniform.

In addition, the accuracy assessment required the consideration of the following general topics: the propagation of errors in a calibration hierarchy, the proper choice of error units, surveys of instrument precision, the evaluation of the significance of various instrument errors, the assessment of the significance of sampling error, and the consideration of methods for demonstrating representative samples and improving instrument precision.

An accuracy assessment considering those factors resulted in the following conclusions:

1. Instrument precision is best expressed as percent of full scale.
2. The proper units for bias errors are percent of point.
3. Calibration-to-calibration repeatability may be utilized to estimate instrument precision.
4. Instrument precision shows wide variations from day-to-day.
5. Correcting past data by post-test calibration adjustments will not, in general, improve emission data altered by instrument drift.
6. Sampling error due to the distribution of emission concentrations in space is the single largest source of uncertainty in emission measurements.

All of the above provide some understanding of the uncertainty in emissions measurement. To ensure complete compliance, the emission control technology is required to reduce the average engine emissions below the Regulation limits by an amount equivalent to the sum of the uncertainty in the measurement and the engine to engine variability. "

On the other hand, Klingenberg et al. ⁽²⁴¹⁾ are critical of the present U. S. regulations for automobile exhaust emissions. They find that no allowance has been made for measuring uncertainties when evaluating the test results and that the final results are not subjected to any form of statistical analysis. They claim that unrecognized systematic errors can be big, but could be "avoided by currently performing correlation tests which should be required by law and specified in the Federal Register. " These criticism are mainly directed to the particular influencing factors in emission tests for automobiles, but emphasize the need for standardization.

7.2 Remote Monitors Providing Line Profile Data

Introduction: The format employed in the following analyses has been chosen to provide to an engineer or scientist sufficient background, typical parameter values and methodology for this individual to perform a preliminary analysis of the suitability of a particular technique to a given measurement problem. It cannot be rigidly applied to every variation of any technique because development in instrument design may simplify (or further complicate) these analyses. It is the responsibility of the evaluation engineer to thoroughly understand the particular instrument under consideration; the following discussions are intended to provide a basis for that understanding.

Because the basic principles vary for these instruments, the discussion format also varies slightly to best suit the particular principle being presented. Basically, the following format is utilized.

Principles of Operation: A basic, brief description of the physical process involved. This is adapted from the more thorough discussion in Section 5.

System Description: A description of the equipment required and their interrelationship. This is often presented as a generalized block diagram plus photos or drawings of existing instruments, where available.

System Parameters: A listing of the more important parameters that the evaluation engineer will encounter, along with their typical values, availability, etc.

This is generally subdivided into the following (not all applies to each instrument).

Sources: Typically lasers or blackbody sources of radiant energy.

Operational Wavelengths: Those wavelength regions and the corresponding pollutant species which are known to be applicable to this technique. Because many of these are still under development (even though an operating instrument may have been built) future investigators will undoubtedly add to the wavelengths and species noted here.

Detector: Current applicable examples are given, however, the state-of-the-art is changing rapidly in this field.

Optics: All of these instruments require optical systems, and all such systems can be characterized by these several parameters. Calculation of these parameters for a particular instrument design--invariance of the quantity $A\Omega$ at all points in the system is assumed here, but if this was neglected, the design performance is degraded and analysis can become complex.

Electronic Bandpass: Expressed as the time required for an instrument to reach 63 percent response to a step change in the measured parameter. Longer times have the effect of increasing the SNR by averaging the noise. When expressed as a frequency Δf it is related to the time constant t_c by

$$\Delta f = 1/4 t_c$$

The numerical constant 4 is typical, but will depend on the electronic design.

Theoretical Performance Prediction: This allows the evaluation engineer to determine whether the instrument can, in principle, perform the desired measurement. Optimum instrument design is assumed (e. g., detector noise limited performance) and any deviation from this optimum will cause degraded performance.

In many cases the required parameters, especially pollutant absorption constants, have not yet been determined and the theoretical

performance predictions cannot be made until these data are published.

Special Requirements: This calls attention to any unusual aspects of the technique to which the evaluation engineer must be aware.

Data Analysis: A basic technique for analysis of the data is presented. This provides a basic understanding of the problem; actual data analysis generally involves more atmospheric parameters than this basic presentation.

7. 2. 1 LWIR Differential Absorption

7. 2. 1. 1 Principle of Operation

The measurement principle of long wavelength infrared (LWIR) differential absorption is used to obtain concentrations as a function of range for ozone and certain hydrocarbons. Laser pulses at two different wavelengths in the 8-12 μm region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the transmission of the pollutants can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7. 2. 1. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) is shown in Figure 7. 2. 1-1. In order to use a heterodyne detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7. 2. 1-2. It should be noted that no prototype

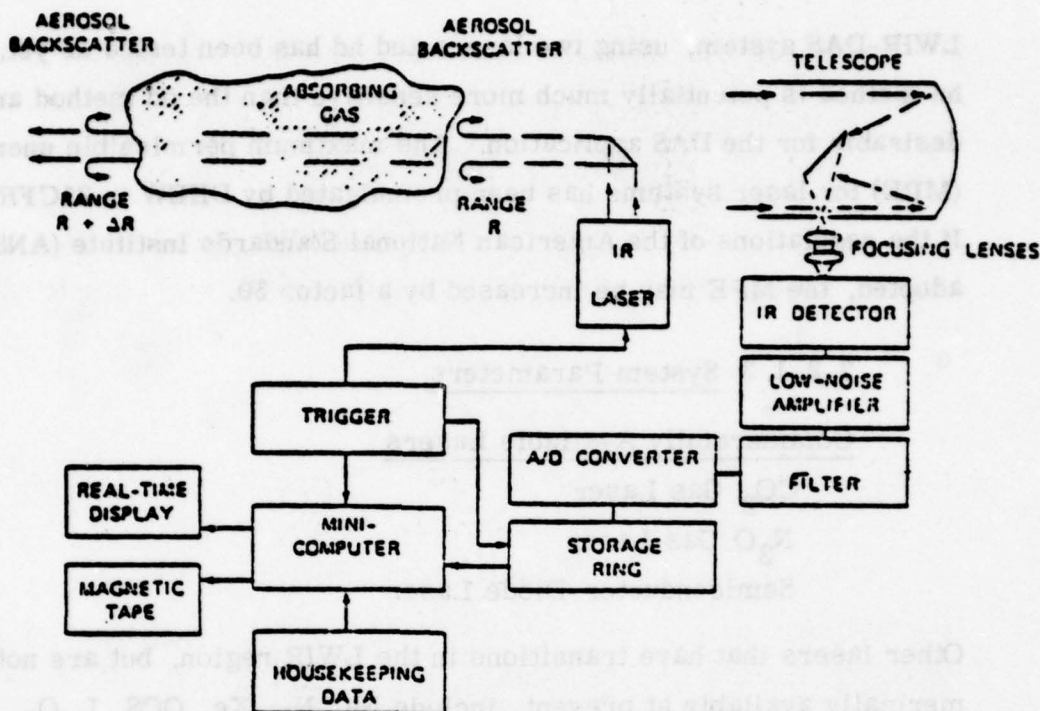


Figure 7.2.1-1. Block Diagram for LWIR DAS System Using Single Laser and Direct Detection (adopted from Ref. 249).

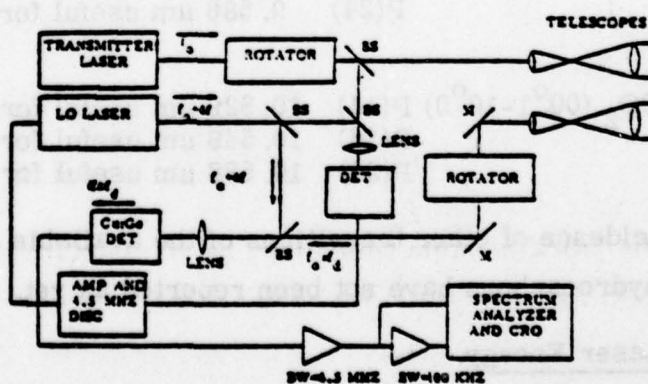


Figure 7.2.1-2. Block Diagram for LWIR DAS System Using Single Laser and Heterodyne Detection (adopted from Ref. 258).

LWIR-DAS system, using two lasers and hd has been tested as yet. The hd method is potentially much more sensitive than the dd method and is desirable for the DAS application. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

7. 2. 1. 3 System Parameters

Commercially Available Lasers

CO₂ Gas Laser

N₂O Gas Laser

Semiconductor-Diode Laser

Other lasers that have transitions in the LWIR region, but are not commercially available at present, include Ne, N₂, Xe, OCS, I, O₂, and HF (Refs. 256 and 257).

Operational Wavelengths

CO ₂ (00 ⁰ 1-02 ⁰ 0)	P(14)	9.504 μm useful for ozone (Ref. 251)
	P(20)	9.552 μm useful for ozone " "
	P(24)	9.586 μm useful for ozone " "

CO ₂ (00 ⁰ 1-10 ⁰ 0)	P(14)	10.529 μm useful for ethylene (Ref. 251)
	P(16)	10.549 μm useful for ethylene " "
	P(20)	10.588 μm useful for ethylene " "

The coincidence of other transitions of the available lasers to ozone and the hydrocarbons have not been reported as yet.

Laser Energy

$2 \times 10^{-4} \text{ J/cm}^2$ for 1-100 ns pulses

$1.1 \times 10^{-2} t^{1/4} \text{ J/cm}^2$ for 100 ns - 10 s pulses

Shortest pulse duration of commercially available CO₂ lasers is 40 nsec, resulting in a resolution element ΔL , of 6 m, and available energy exceeds MPE by orders of magnitude. ANSI regulations would permit 50 fold increase in laser energy.

Detector

Commercially available detectors with highest D* and shortest risetimes at operating temperatures of 77K are

Lead-Tin-Telluride ($D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$, $t_c \sim 10 \text{ ns}$)

Mercury-Cadmium-Telluride ($D^* \sim 3 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$, $t_c < 1 \text{ ns}$)

These detectors can be made to peak anywhere in the region from 8-12 μm . Active detector areas can range from 0.0025 to 1 mm^2 .

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (=A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ($A_o \Omega_o \approx \lambda^2$).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c} = \frac{1}{4nt_s}$$

where t_s is the pulse duration. The number of pulses to be sampled is a variable that can be used to increase the SNR.

7.2.1.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by DAS is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2 + (1/P_2)^2 + (1/P_2')^2}}$$

where

$$\ln Q^1 = \ln \frac{P_1 P_2'}{P_1' P_2}$$

$$P_1 = (G/R^2) e^{-2k_1 C R}$$

$$P_1' = (G/(R + \Delta R)^2) e^{-2k_1 C (R + \Delta R)}$$

$$P_2 = (G/R^2) e^{-2k_2 C R}$$

$$P_2' = (G/(R + \Delta R)^2) e^{-2k_2 C (R + \Delta R)}$$

$$G = \eta P_t \Delta R N(R) \beta A_o$$

$$dP = \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left(\frac{A_d}{4n\tau_s} \right)^{1/2} (D^*)^{-1}/F$$

$$F = \eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} h c D^*$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{2 \text{NEP}/F}$$

where

$$Q = 2(k_1 C - k_2 C) \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

$$\text{Assume: } D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

$$F \approx 100 \text{ for heterodyne detection}$$

Result: Plot in Figure 7. 2. 1-3 shows NEP/F versus A_d for different number of pulses n .

Step 2: Calculate: G

$$\text{Assume: } N(R)\beta \approx 8 \times 10^{-8} \text{ cm}^{-1} \text{ ster}^{-1}$$

$$\Delta R = 1500 \text{ cm}$$

$$P_t = 2 \times 10^4 \text{ W for a } 2 \times 10^{-3} \text{ J laser, having a } 10 \text{ cm}^2 \text{ beam area and a pulse duration of 100 nsec}$$

Result: Plot in Figure 7. 2. 1-4 shows G versus receiver aperture area A_o for three values of overall efficiency (optical and mechanical shutters)

Step 3: Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

$$\text{Assume: } kC = 0, .3, 1, 3 \text{ km}^{-1}$$

Result: Plot in Figure 7. 2. 1-5 shows $\xi(R)$ versus R for the above values of kC

Step 4: Calculate: $P_{\text{eff}} = G \xi(R)$

$$\text{Assume: Useful range of } R \text{ between 100 and 1000 m}$$

Result: Plot in Figure 7. 2. 1-6 which shows P_{eff} vs. $\xi(R)$ for different values of G .

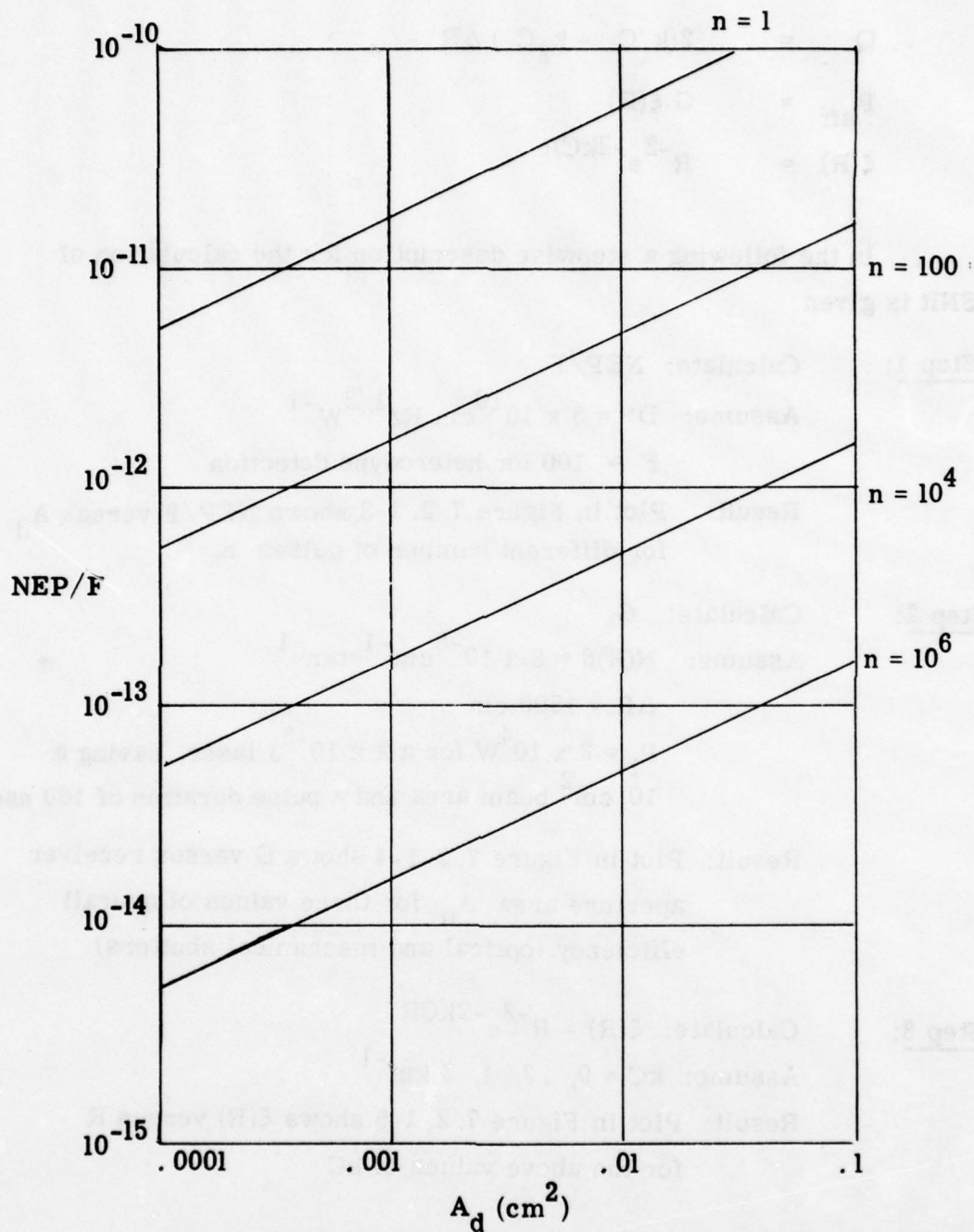


Figure 7.2.1-3. NEP versus A_d for Different Values of Number of d Pulses, Assuming $D^* = 3 \times 10^{10} \text{ cmH}^2\text{W}^{-1}$ and $t_s = 100 \text{ ns}$.

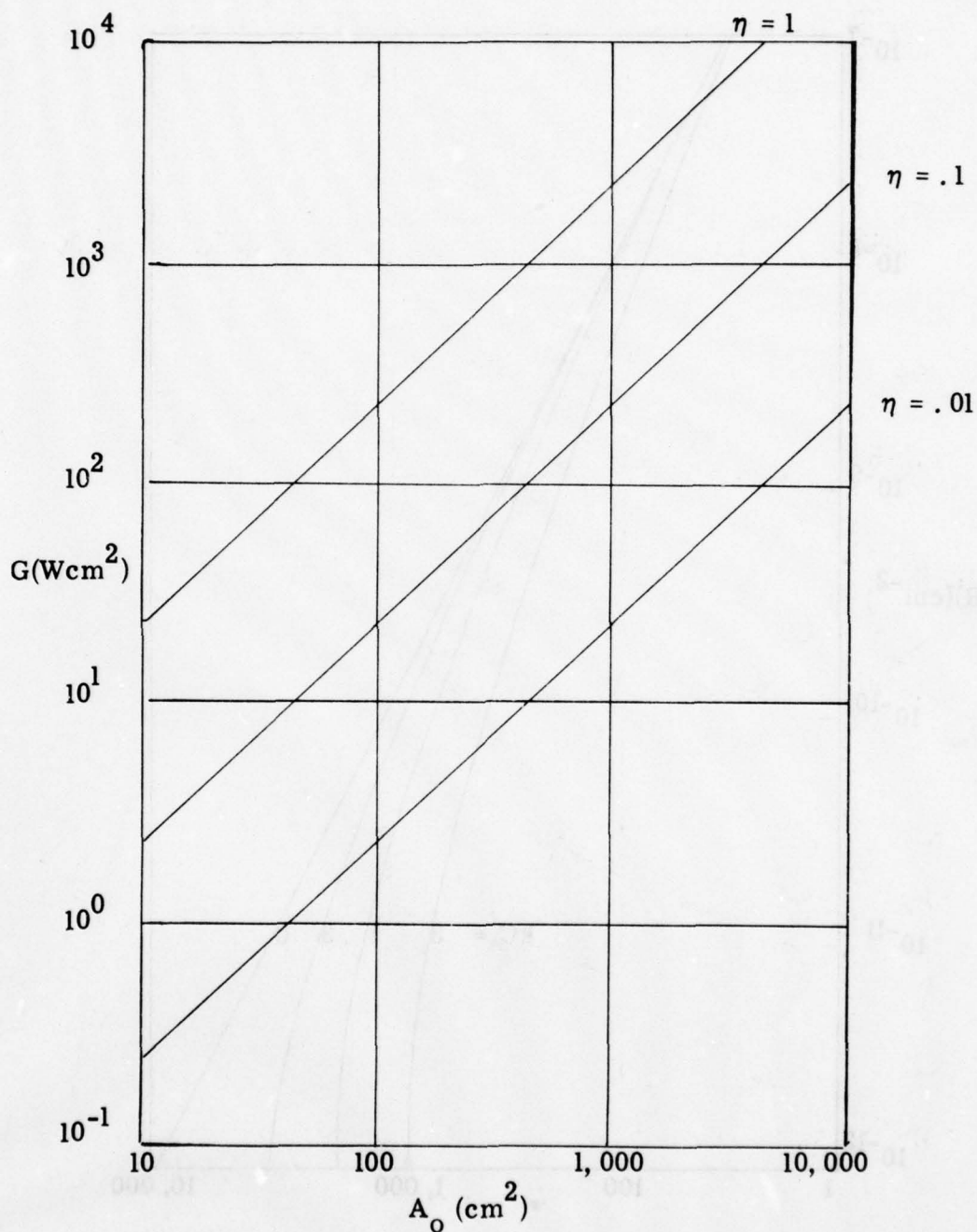


Figure 7. 2. 1-4. Function G versus A_0 for Three Values of η , using $\Delta R = 15 \text{ m}$, $N(R)\beta = 8 \times 10^{-8} \text{ cm}^{-1}\text{ster}^{-1}$ and $P_t = 2 \times 10^{-3} \text{ J}$ for 10 cm^2 laser beam area.

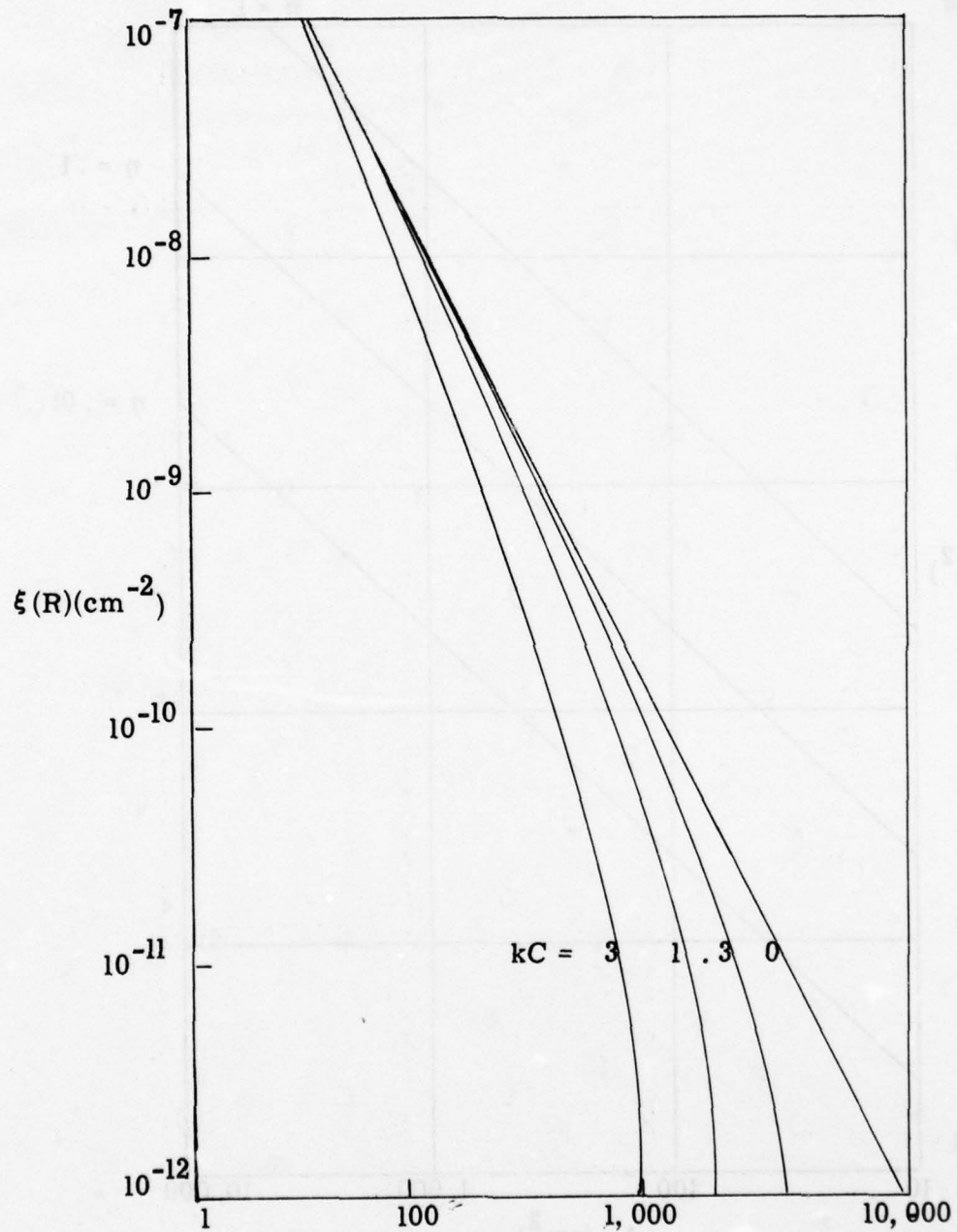


Figure 7. 2. 1-5. Function $\xi(R)$ vs. Range for Different Values of kC (km^{-1})

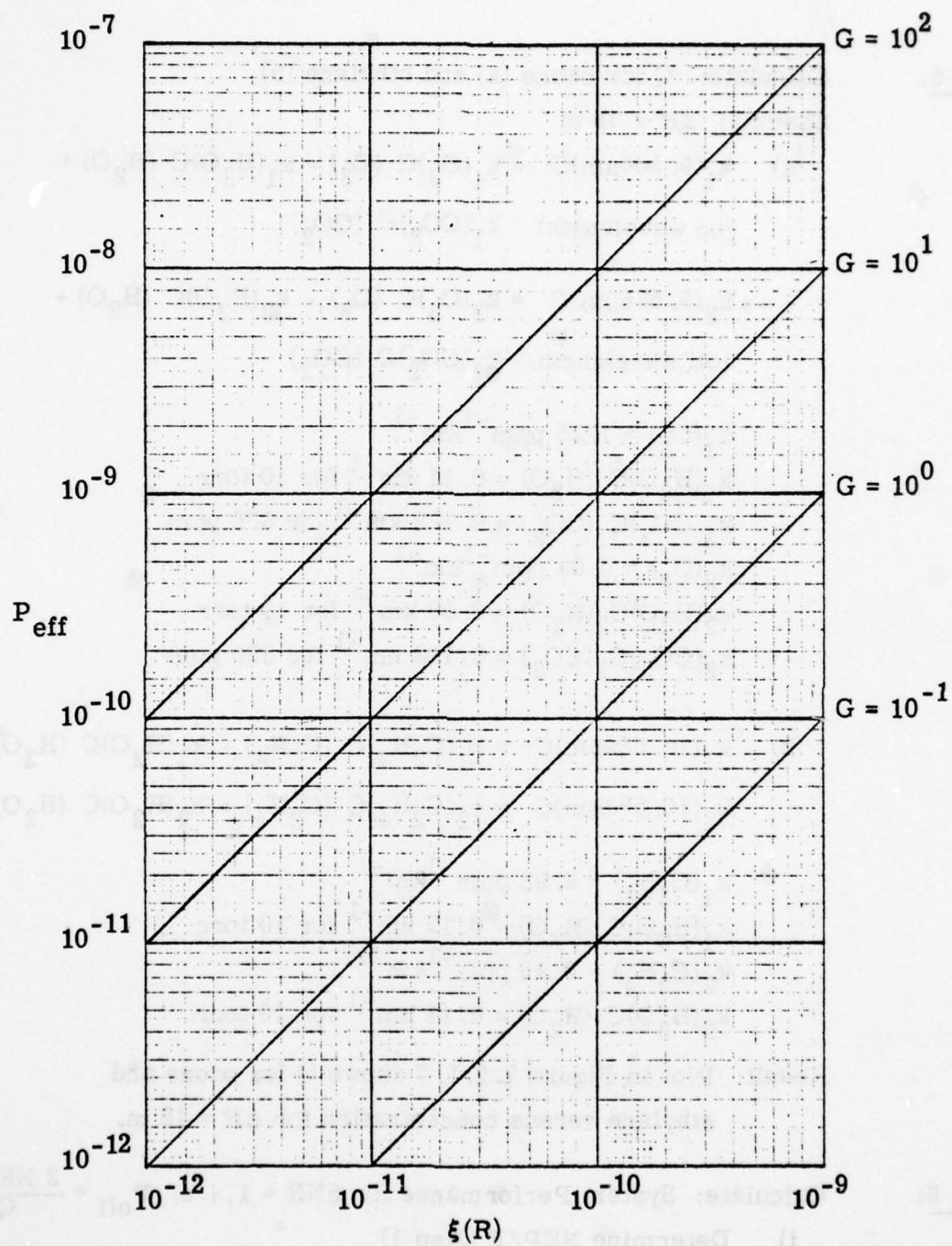


Figure 7. 2. 1-6. P_{eff} vs. the Function $\xi(R)$ for Different Values of G

Step 5: Calculate: Q for ozone (a) and ethylene (b)

Assume: $\Delta R = 15$ m

$$\text{a) } k_1(9.504\mu\text{m})C = k_1(\text{O}_3)C(\text{O}_3) + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) + \\ (\text{on wavelength}) \quad k_1(\text{CO}_2)C(\text{CO}_2)$$

$$k_2(9.586\mu\text{m})C = k_2(\text{O}_3)C(\text{O}_3) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) + \\ (\text{off wavelength}) \quad k_2(\text{CO}_2)C(\text{CO}_2)$$

$$k_1(\text{O}_3) = 1.25 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.11 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_1(\text{CO}_2)C(\text{CO}_2) = 0.123 \text{ km}^{-1} \text{ for 330 ppm}$$

$$k_2(\text{O}_3) = 0.08 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.09 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{CO}_2)C(\text{CO}_2) = 0.112 \text{ km}^{-1} \text{ for 330 ppm}$$

$$\text{b) } k_1(10.529\mu\text{m})C = k_1(\text{C}_2\text{H}_4)C(\text{C}_2\text{H}_4) + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_2(10.588\mu\text{m})C = k_2(\text{C}_2\text{H}_4)C(\text{C}_2\text{H}_4) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_1(\text{C}_2\text{H}_4) = 2.98 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.12 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{C}_2\text{H}_4) = 0.15 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.11 \text{ km}^{-1} \text{ for 10 torr}$$

Result: Plot in Figure 7. 2. 1. 7 shows Q for ozone and ethylene versus concentration for $\Delta R = 15$ m.

Step 6:

Calculate: System Performance for $\text{SNR} = 1$, i. e., $P_{\text{eff}} = \frac{2 \text{ NEP}/F}{Q}$

i) Determine NEP/F (Step 1)

ii) Calculate Q for desired concentration (Step 5, Figure 7. 2. 1 -7)

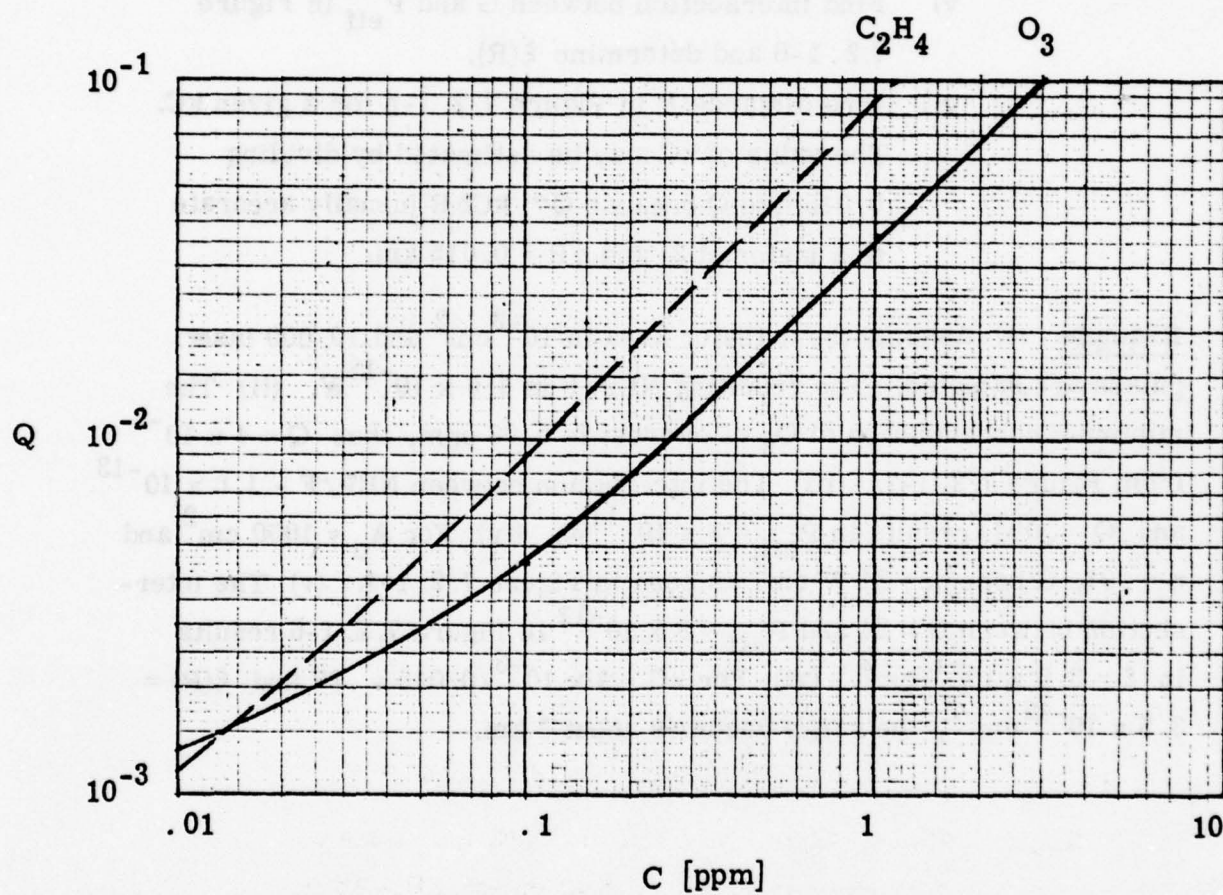


Figure 7. 2. 1 -7. Q versus Concentration of Ozone and Ethylene for a Resolution Element of 15 m.

- iii) Locate intersection between NEP/F and Q in Figure 7.2.1-8 and determine P_{eff} . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7.2.1-4.
- v) Find intersection between G and P_{eff} in Figure 7.2.1-6 and determine $\xi(R)$.
- vi) Find distance R in Figure 7.2.1-5 for a given kC. The value of kC may be estimated by dividing 0.015 into Q because $Q \approx kC \Delta R$ (usually accurate to a factor of 2) and $\Delta R = 0.015$ km.

Example (i) Assume the detector area is 10^{-3} cm^2 and 10,000 laser pulses are sampled. The resulting NEP/F is $1.6 \times 10^{-13} \text{ W}$. (ii) The minimum concentration of O_3 of interest is 0.08 ppm, thus $Q = 4 \times 10^{-3}$ from Figure 7.2.1-7. (iii) The intersection between NEP/F - 1.6×10^{-13} and $Q = .004$ results in $P_{\text{eff}_2} = 8 \times 10^{-11} \text{ W}$. (iv) For $A_o = 1000 \text{ cm}^2$ and $\eta = .01$, G becomes 24 W cm^2 as seen in Figure 7.2.1-4. (v) The intersection between $G = 24$ and $P_{\text{eff}} = 8 \times 10^{-11}$ in Figure 7.2.1-6 results in $\xi = 3.5 \times 10^{-12} \text{ cm}^2$. (vi) For $kC = 4 \times 10^{-3} / 0.015 = .27$ and $\xi(R) = 3.5 \times 10^{-12} \text{ cm}^2$, the range becomes about 3 km.

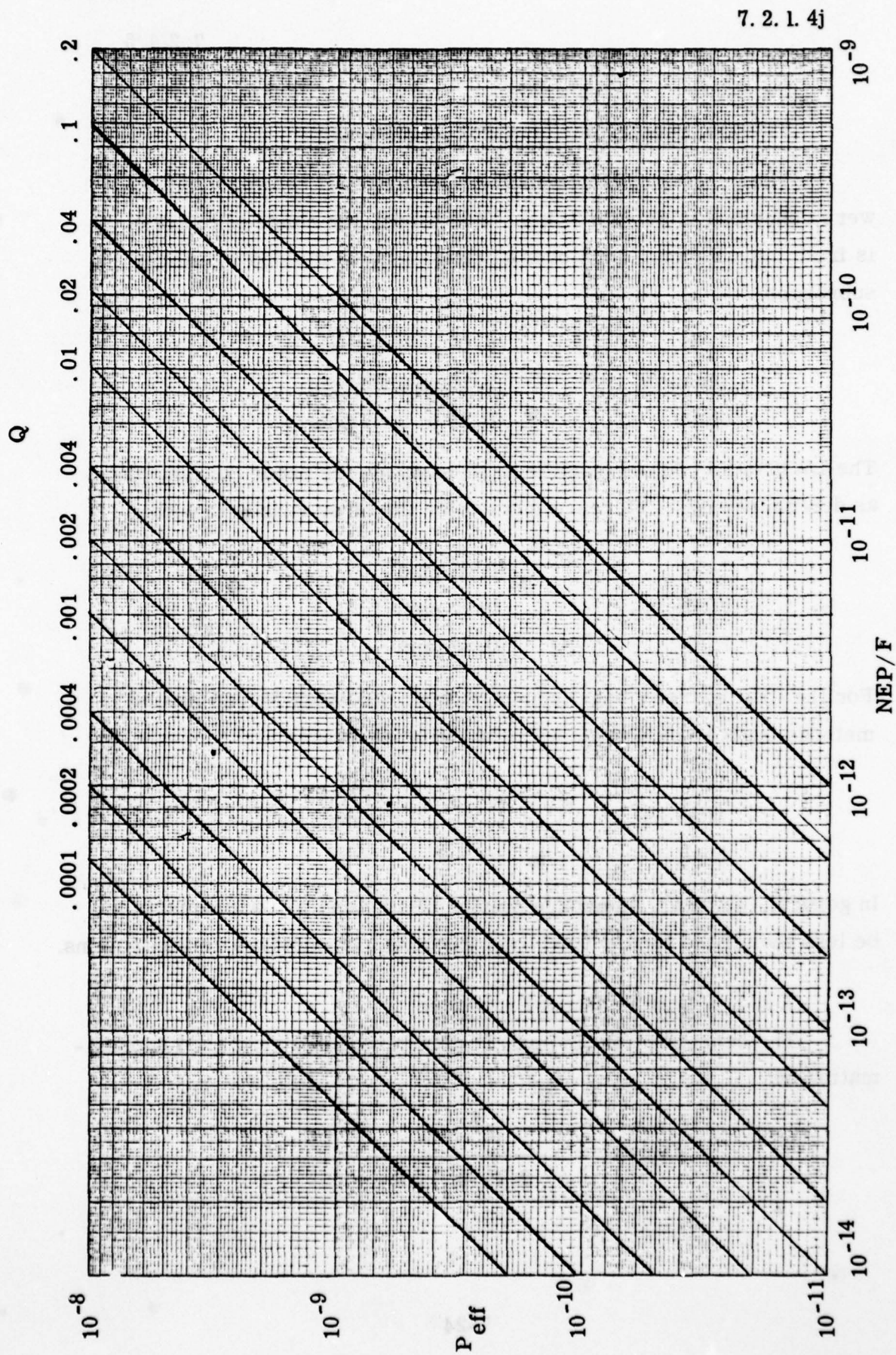


Figure 7. 2. 1 -8. P_{eff} versus NEP/F for Different Values of Q .

7. 2. 1. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. For ozone, the range of interest is from 0 to . 5 ppm. This overall range may be divided into three subranges:

Low	0. 06 to 0. 10 ppm
Medium	0. 15 to 0. 25 ppm
High	0. 35 to 0. 45 ppm

The LWIR-DAS remote monitor must measure the ozone concentration as determined by a reference method for the three ranges to within

Low	0. 02 ppm
Medium	0. 03 ppm
High	0. 04 ppm

For the total hydrocarbons (non-methane), the range for automated methods ought to be 2 ppm, with the following ranges

Low	. 2 - . 28 ppm
Medium	. 5 - . 6 ppm
High	1 - 2 ppm

In general, however, the concentration of ethylene will appreciably be less than those for the total hydrocarbons/non-methane concentrations.

7. 2. 1. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Figure 7. 2. 1-9 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams with the abscissa shown in units of range. The four signals are determined from analog signals as given in Figure 7. 2. 1-9. The absorption coefficients k_1 and k_2 are as follows:

	Ozone	Ethylene
$k_1(\text{ppmkm})^{-1}$	1.25 @ 9.504 μm	2.98 @ 10.529 μm
$k_2(\text{ppmkm})^{-1}$	0.08 @ 9.586 μm	0.15 @ 10.588 μm

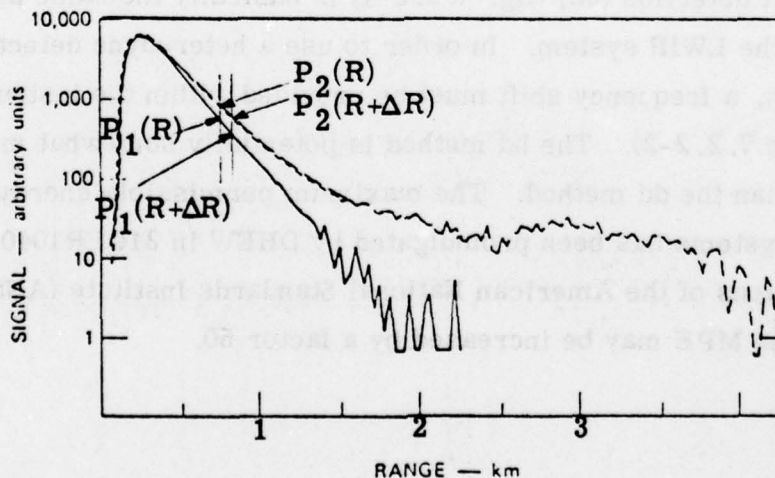


Figure 7. 2. 1-9. Analog Signals $P_1(R)$, $P_2(R)$, $P_1(R+\Delta R)$ and $P_2(R+\Delta R)$

7. 2. 2 MWIR-DAS

7. 2. 2. 1 Principle of Operation

The measurement principle of medium wavelength infrared (MWIR) differential absorption is used to obtain range-resolved concentrations of carbon monoxide and nitrous oxide. Laser pulses at two different wavelengths in the 4.8-5.4 μm region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the transmission of the pollutants can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7. 2. 2. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) (fig. 7. 2. 2-1) is basically the same as was shown for the LWIR system. In order to use a heterodyne detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7. 2. 2-2). The hd method is potentially somewhat more sensitive than the dd method. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

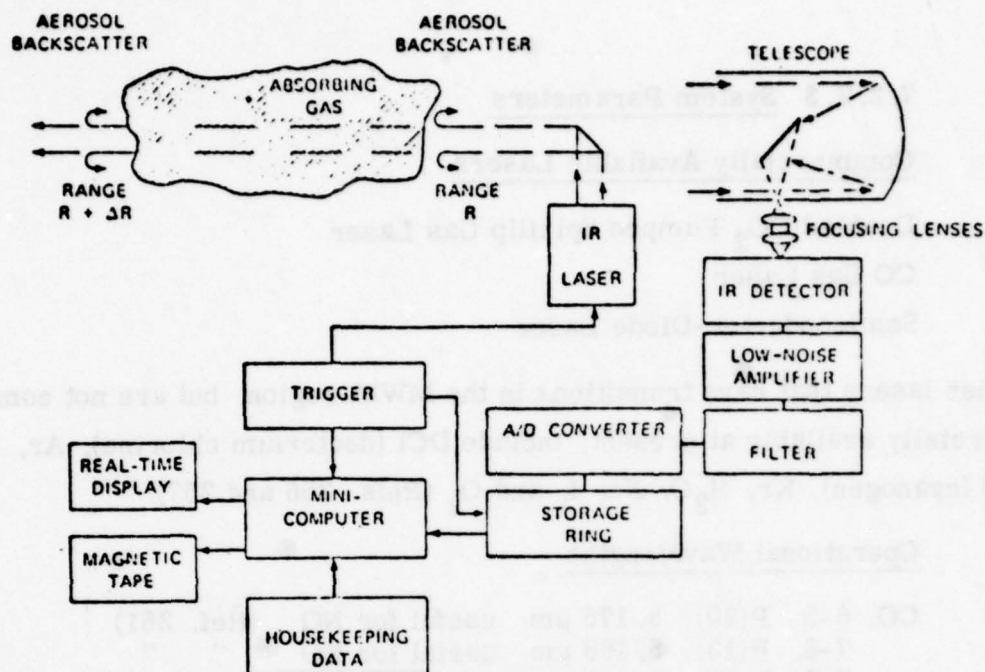


Figure 7.2. 2-1. Block Diagram for MWIR DAS System Using Single Laser and Direct Detection (adopted from Ref. 249).

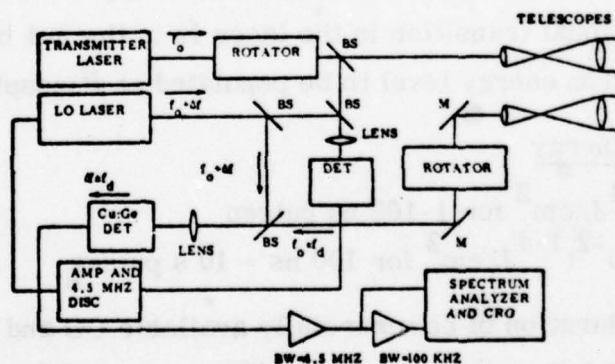


Figure 7.2. 2-2. Block Diagram for MWIR DAS System Using Single Laser and Heterodyne Detection (adopted from Ref. 258).

7. 2. 2. 3 System Parameters

Commercially Available Lasers

Doubled CO₂ Pumped Spinflip Gas Laser

CO Gas Laser

Semiconductor-Diode Laser

Other lasers that have transitions in the MWIR region, but are not commercially available at present, include DCl (deuterium chlorine), Ar, CN (cyanogen), Kr, H₂O, Xe, I, and O₂ (Refs. 256 and 257).

Operational Wavelengths

CO, 6-5, P(20)	5.176 μm	useful for NO	(Ref. 251)
7-6, P(13)	5.166 μm	useful for NO	" "
7-6, P(15)	5.187 μm	useful for NO	" "
9-8, P(9)	5.262 μm	useful for NO	" "

The coincidence of other transitions of the available lasers to carbon monoxide and nitrous oxide have not been reported as yet. The CO gas laser cannot be used to observe CO in the atmosphere since the lowest observed vibrational transition in the laser is in the 5-4 band [P(18) and up], which is too high an energy level to be populated at atmospheric temperatures.

Laser Energy

$2 \times 10^{-4} \text{ J/cm}^2$ for 1-100 ns pulses

$1.1 \times 10^{-2} t^{1/4} \text{ J/cm}^2$ for 100 ns - 10 s pulses

Shortest pulse duration of commercially available CO and doubled CO₂ pumped spin flip lasers are 1 μsec and 200 ns, respectively. In order to obtain a resolution element of 15 m, the gating time of the receiver can be adjusted to 100 nsec.

Detector

Commercially available detectors with highest D^* and shortest risetimes at operating temperatures of 77K are

Indium-Antimonide ($D^* \sim 10^{11} \text{ cm Hz}^{1/2}/\text{W}$, $t < 1\mu\text{s}$)

Gold-doped Germanium ($D^* \sim 2 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$, $t \sim 1\mu\text{s}$)

Active detector areas can range from 0.008 to 1 mm^2 .

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_o
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ($A_o \Omega_o \approx \lambda^2$).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c} = \frac{1}{4nt_s}$$

where t_s is the pulse duration. The number of pulses to be sampled is a variable that can be used to increase the SNR.

7.2.2.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by DAS is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2 + (1/P_2)^2 + (1/P_2')^2}}$$

where

$$\ln Q^1 = \ln \frac{P_1 P_2'}{P_1' P_2}$$

$$P_1 = (G/R^2) e^{-2k_1 C R}$$

$$P_1' = (G/(R + \Delta R)^2) e^{-2k_1 C (R + \Delta R)}$$

$$P_2 = (G/R^2) e^{-2k_2 C R}$$

$$P_2' = (G/(R + \Delta R)^2) e^{-2k_2 C (R + \Delta R)}$$

$$G = \eta P_t \Delta R N(R) \beta A_o$$

$$dP = \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left(\frac{A_d}{4 n t_s} \right)^{1/2} (D^*)^{-1}/F$$

$$F = \eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} h c D^*$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{2 \text{NEP}/F}$$

where

$$Q = 2(k_1 C_1 - k_2 C_2) \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1:

Calculate: NEP/F

Assume: $D^* = 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$

$F = 10$ for heterodyne detection

$t_s = 100 \text{ nsec}$

Result: Plot in Figure 7. 2. 2-3 shows NEP/F versus A_d for different number of pulses n .

Step 2:

Calculate: G

Assume: $N(R)\beta \approx 8 \times 10^{-8} \text{ cm}^{-1} \text{ ster}^{-1}$

$\Delta R = 1500 \text{ cm}$

$P_t = 2 \times 10^4 \text{ W}$ for a $2 \times 10^{-3} \text{ J}$ laser, having a 10 cm^2 beam area and a pulse duration of 100 nsec

Result: Plot in Figure 7. 2. 2 -4 shows G versus receiver aperture area A_o for three values of overall efficiency (optical and mechanical shutters)

Step 3:

Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 2. 2-5 shows $\xi(R)$ versus R for the above values of kC

Step 4:

Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7. 2. 2-6 which shows P_{eff} vs. $\xi(R)$ for different values of G .

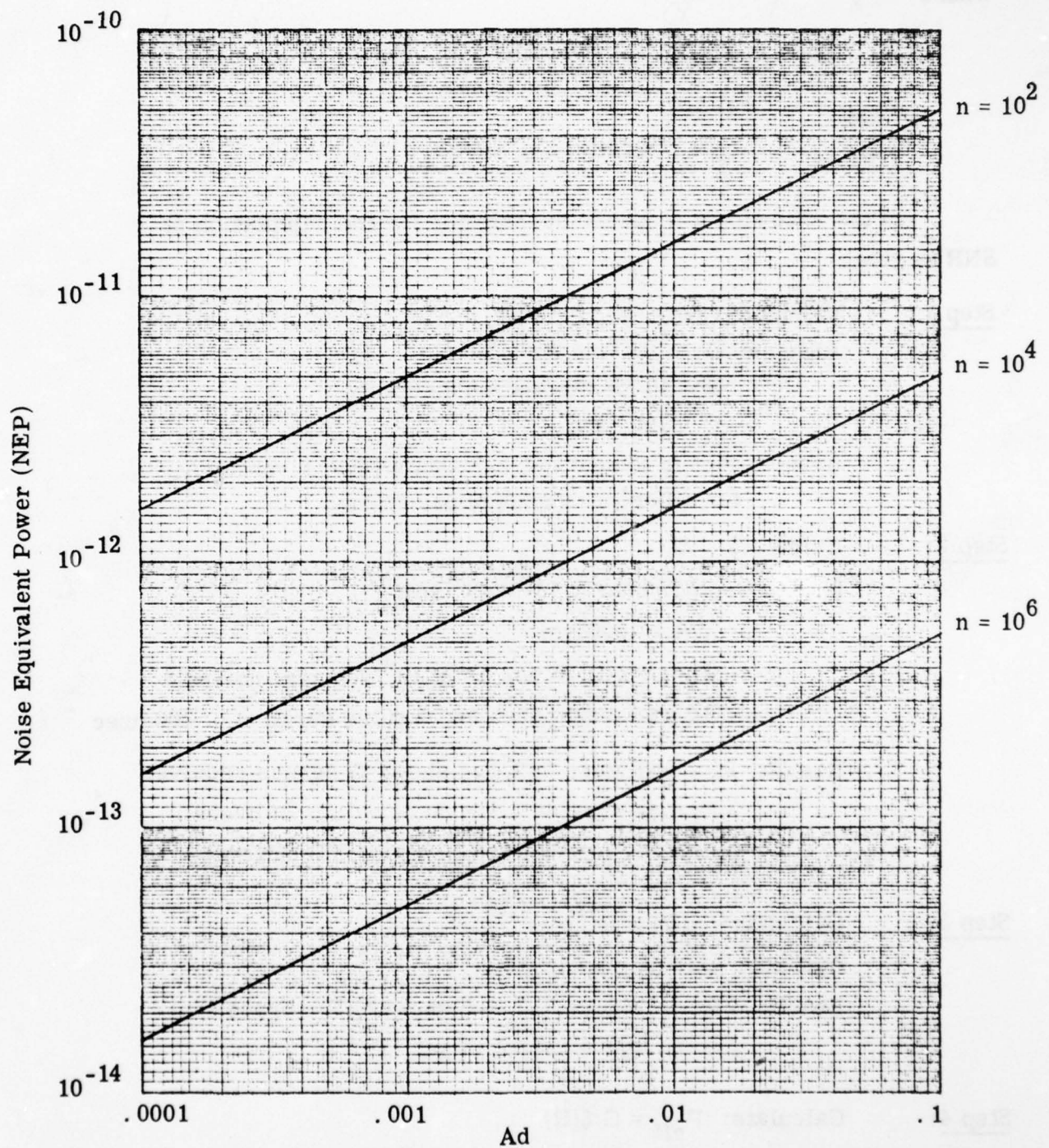


Figure 7. 2. 2-3. NEP versus A_d for Different Values of Number of Pulses, Assuming $D^* = 10^{11} \text{ cm H}^{1/2} \text{ W}^{-1}$ and $t_s = 100 \text{ ns}$.

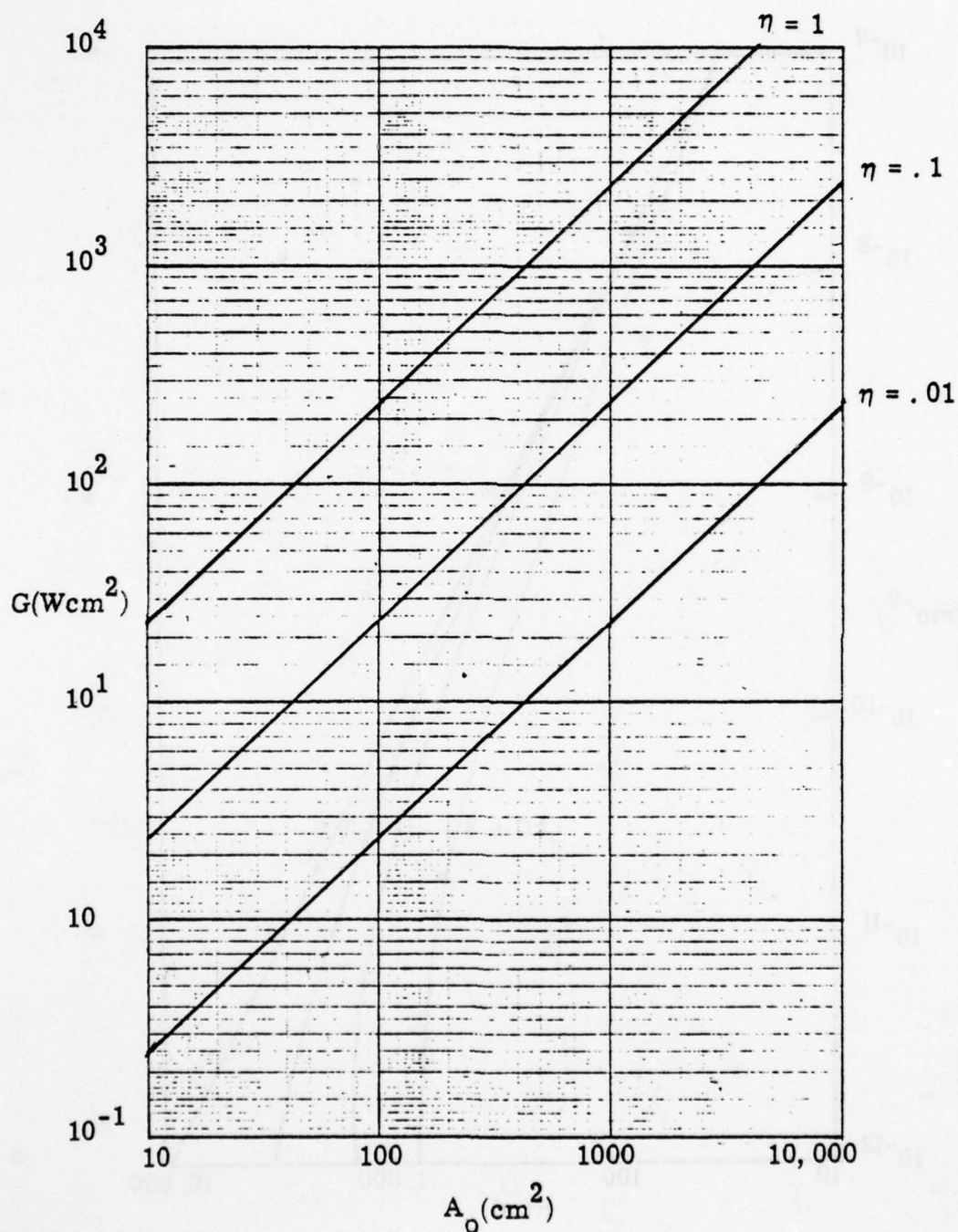


Figure 7. 2. 2-4. Function G versus A_0 for Three Values of η , using $\Delta R = 15 \text{ m}$, $N(R)\beta = 8 \times 10^{-8} \text{ cm}^{-1}\text{ster}^{-1}$ and $P_t = 2 \times 10^{-3} \text{ J}$ for 10 cm^2 laser beam area.

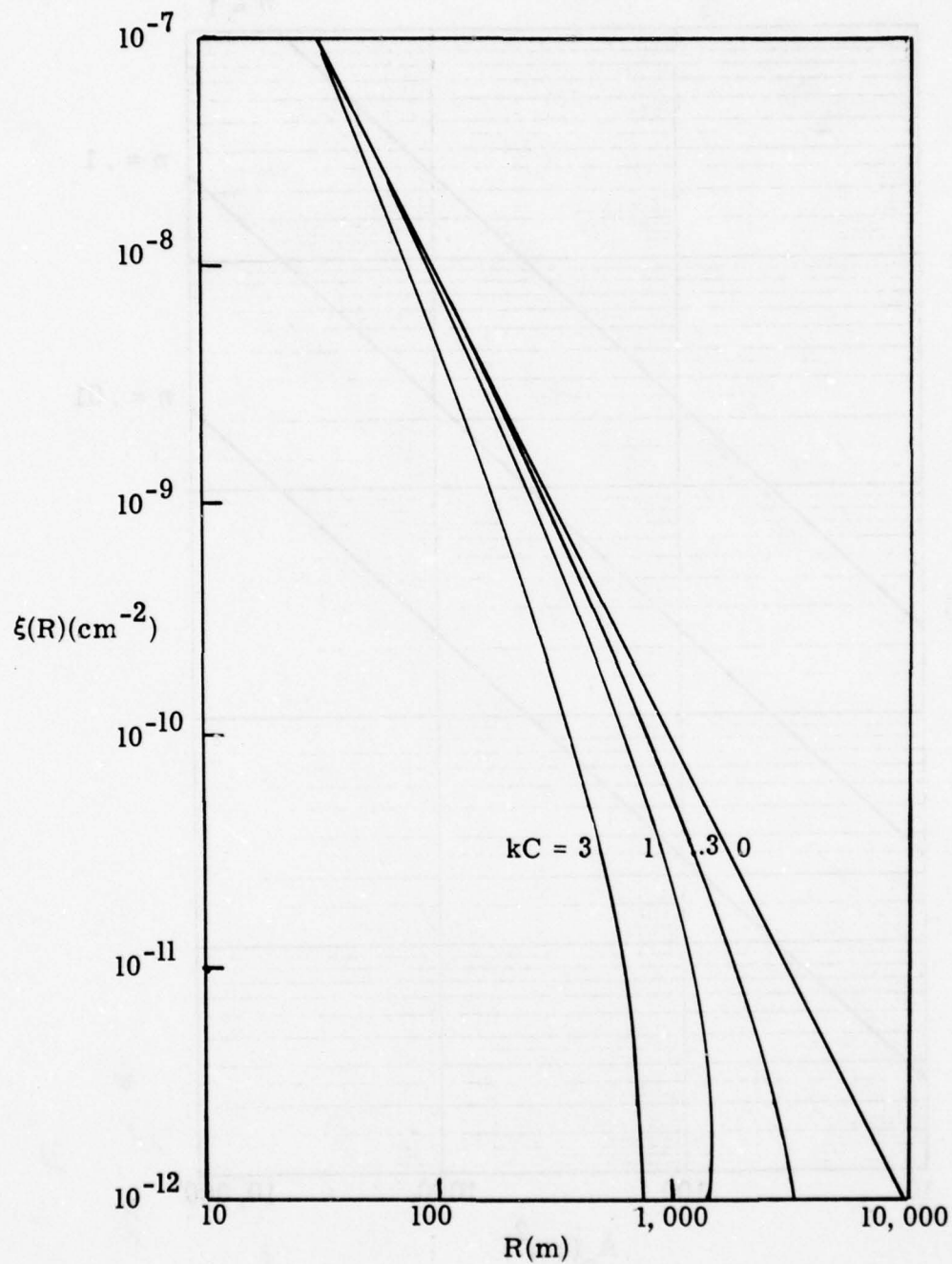


Figure 7. 2. 2-5. Function $\xi(R)$ vs. Range for Different Values of kC (km^{-1})

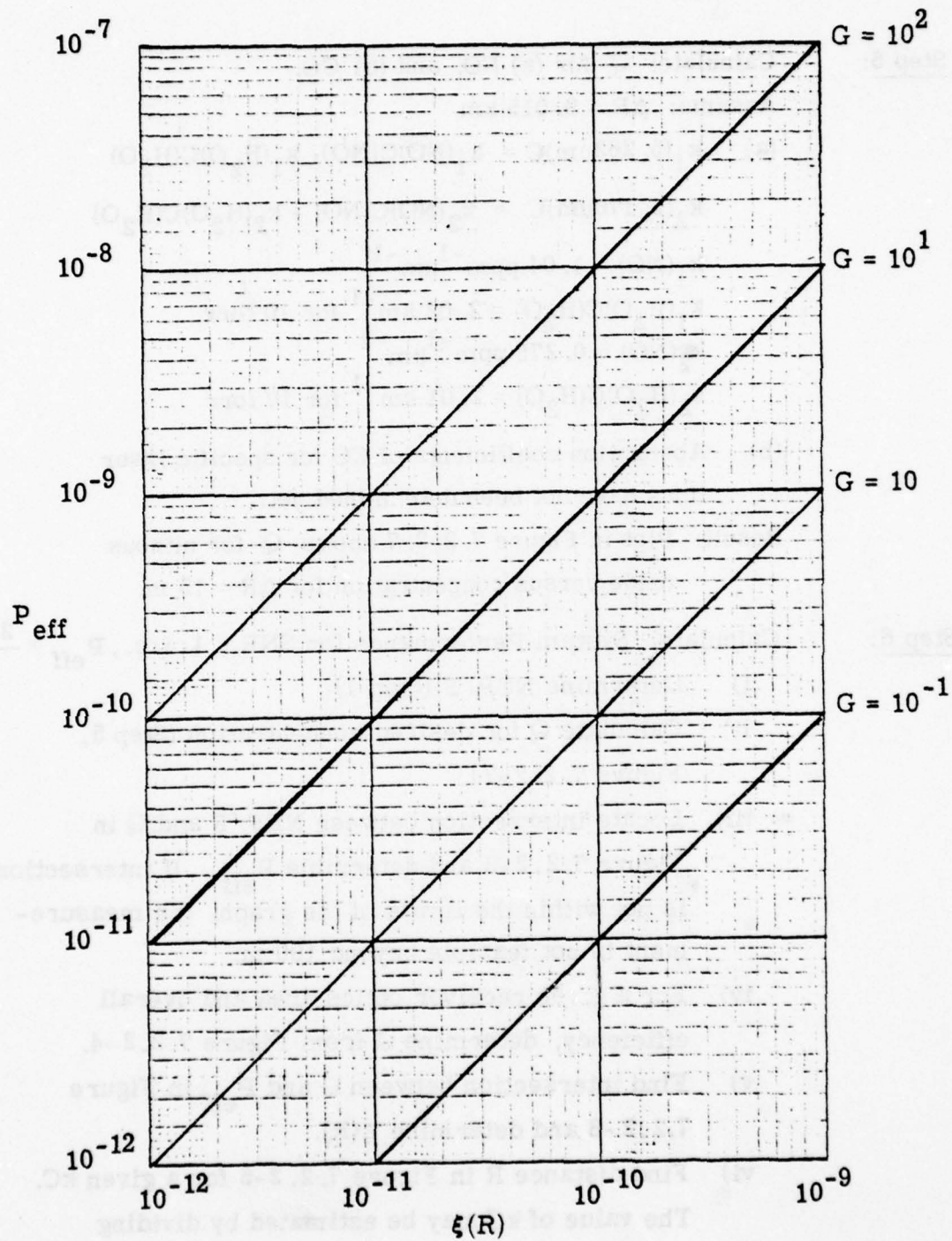


Figure 7. 2. 2 -6. P_{eff} vs. the Function $\xi(R)$ for Different Values of G

Step 5:

Calculate: Q for (a) NO, and (b) CO.

Assume: $\Delta R = 0.015$ km

$$(a) \quad k_1(5.262\mu\text{m})C = k_1(\text{NO})C(\text{NO}) + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_2(5.176\mu\text{m})C = k_2(\text{NO})C(\text{NO}) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_1(\text{NO}) = 1.04 \text{ ppm}^{-1} \text{ km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 2.02 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{NO}) = 0.275 \text{ ppm}^{-1} \text{ km}^{-1}$$

$$k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 2.01 \text{ km}^{-1} \text{ for 10 torr}$$

- (b) Absorption coefficients of CO for specific laser lines have not been determined yet.

Result: Plot in Figure 7.2.2.7 shows Q for nitrous oxide versus concentration for $\Delta R = 15$ m.

Step 6:

Calculate: System Performance for $\text{SNR} = 1$, i. e., $P_{\text{eff}} = \frac{2 \text{ NEP}/F}{Q}$

- i) Determine NEP/F (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7.2.2-7)
- iii) Locate intersection between NEP/F and Q in Figure 7.2.2-8 and determine P_{eff} . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7.2.2-4.
- v) Find intersection between G and P_{eff} in Figure 7.2.2-6 and determine $\xi(R)$.
- vi) Find distance R in Figure 7.2.2-5 for a given kC . The value of kC may be estimated by dividing 0.015 into Q , because $Q \approx kC\Delta R$ and $\Delta R = 0.015$ km.

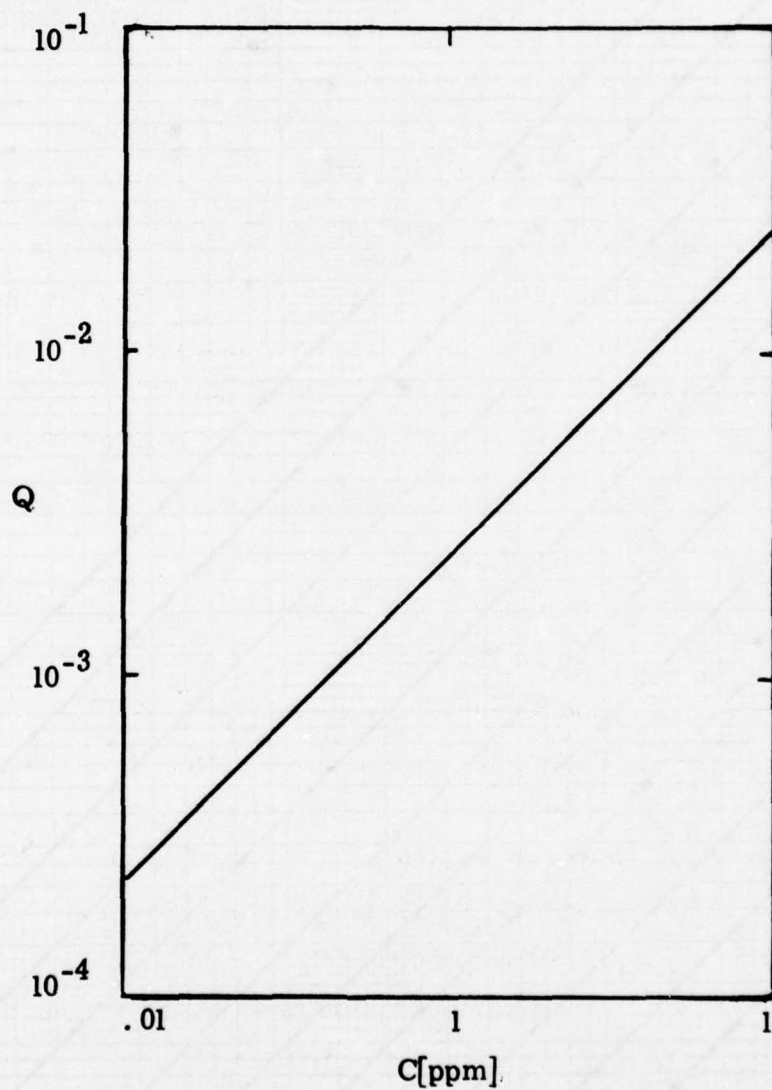


Figure 7. 2. 2-7. Q versus Concentration of NO for a Resolution Element of 15 m.

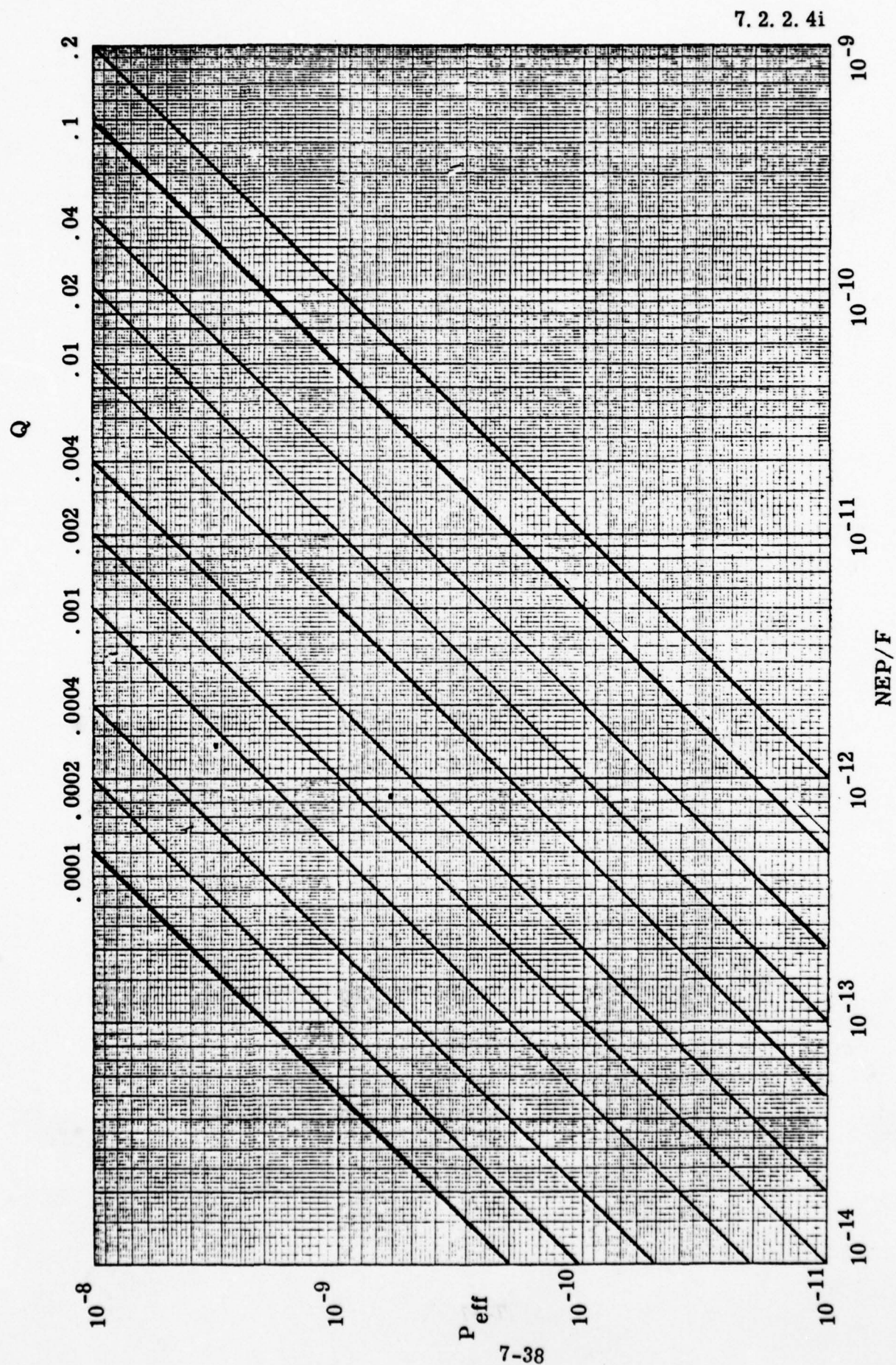


Figure 7. 2. 2-8. P_{eff} versus NEP/F for Different Values of Q .

7. 2. 2. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. For NO_x , the range of interest is from 0 to .35 ppm. This overall range may be divided into three subranges:

Low	0. 02 to 0. 08 ppm
Medium	0. 10 to 0. 20 ppm
High	0. 25 to 0. 35 ppm

However, the concentrations for NO are expected to be less than those of NO_x . The MWIR-DAS remote monitor must measure the NO_x concentration as determined by a reference method for the three ranges to within

Low	0. 02 ppm
Medium	0. 02 ppm
High	0. 03 ppm

For carbon monoxide, the range for automated methods must be 45 ppm with the following ranges

Low	7-11 ppm
Medium	20-30 ppm
High	35-45 ppm

7. 2. 2. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Fig. 7. 2. 2-9 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams as a function of range. The four signals are determined from analog signals as given in Figure 7. 2. 2-9. The absorption coefficients k_1 and k_2 are as follows:

	NO	CO
$k_1(\text{ppmkm})^{-1}$	1.04 @ 5.262 μm	Absorption coefficients of CO for these laser lines are not yet known.
$k_2(\text{ppmkm})^{-2}$	0.275 @ 5.176 μm	

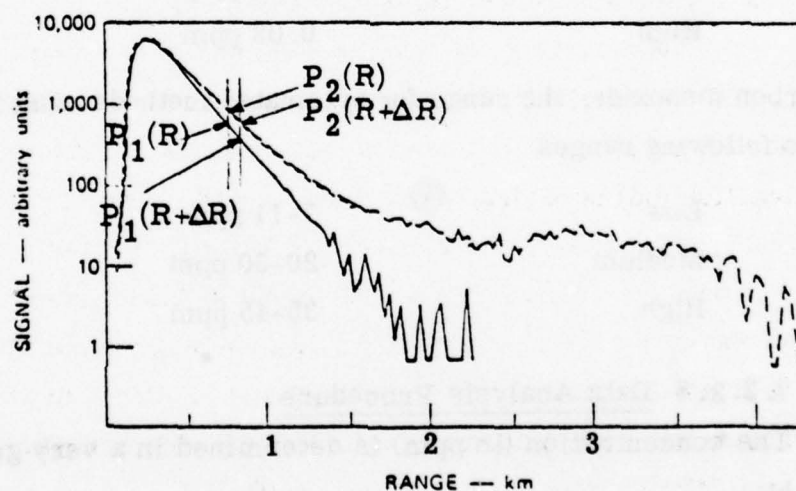


Figure 7. 2. 2-9. Analog Signals $P_1(R)$, $P_2(R)$, $P_1(R+\Delta R)$ and $P_2(R+\Delta R)$

7. 2. 3 SWIR Differential Absorption

7. 2. 3. 1 Principle of Operation

The measurement principle of short wavelength infrared (SWIR) differential absorption is used to obtain range-resolved concentrations of NO_x , SO_2 and hydrocarbons. Laser pulses at two different wavelengths in the 2.5-4.0 μm region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the pollutants transmission can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7. 2. 3. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct direction (dd) is basically the same as was shown for the LWIR system in Figure 7. 2. 3-1. Heterodyne detection (hd) is not useful for SWIR. It should be noted that no prototype SWIR-DAS system, using two lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

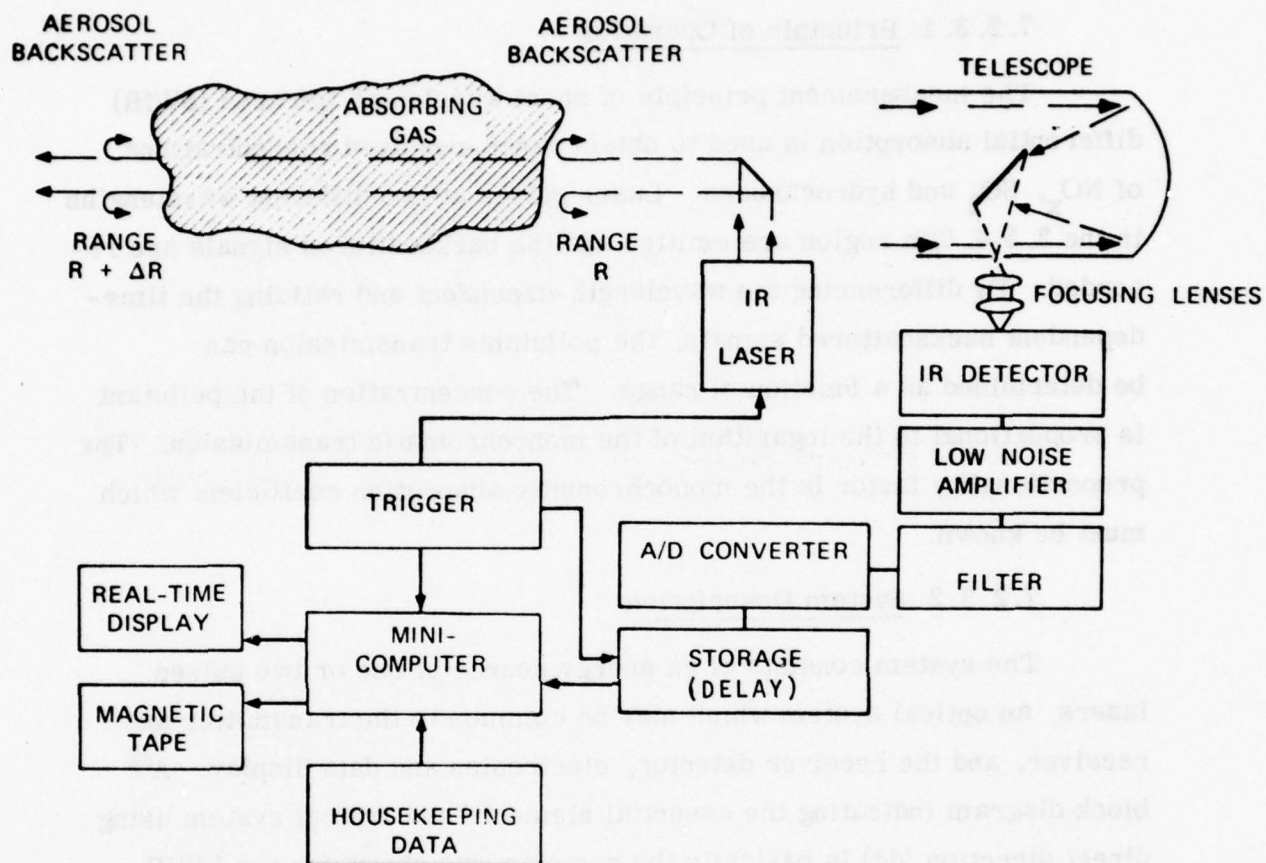


Figure 7. 2. 3-1. Block Diagram for SWIR DAS System Using Single Laser and Direct Detection (adopted from Ref. 249).

7. 2. 3. 3 System Parameters

Commercially Available Lasers

HF Gas Laser

DF Gas Laser

Other lasers that have transitions in the SWIR region, but are not commercially available at present, include Kr, Ne, Ar, I, Xe, Br, O₂, Cl, Cs, N₂, C, HCl and HBr (Refs. 256 and 257).

Operational Wavelengths

Have not been determined yet. These wavelengths will determine which of the above lasers are actually usable for this technique.

Laser Energy

$2 \times 10^{-4} \text{ J/cm}^2$ for 1-100 ns pulses

$1.1 \times 10^{-2} t^{1/4} \text{ J/cm}^2$ for 100 ns - 10 s pulses

Shortest pulse duration of commercially available HF and DF lasers is 500 nsec and 300 nsec, respectively. In order to obtain a resolution element of 15 m, this will need to be reduced to 100 nsec. However, there are no sensitive detectors available with such short rise times. Available energy exceeds MPE by orders of magnitude. ANSI regulations would permit 50 fold increase in laser energy.

Detector

Commercially available detectors with highest D* and shortest risetimes at operating temperatures of 200K are

Lead-Sulfide ($D^* \sim 2 \times 10^9 \text{ cm Hz}^{1/2} / \text{W}$, $t_c \sim 3 \text{ } \mu\text{sec}$, $\lambda_{\text{max}} = 3.5 \text{ } \mu\text{m}$)
 ($D^* \sim 2.5 \times 10^9 \text{ cm Hz}^{1/2} / \text{W}$, $t_c \sim 1 \text{ } \mu\text{sec}$, $\lambda_{\text{max}} = 4 \text{ } \mu\text{m}$)

Active areas can range from 0.001 to 8 mm² for the detector peaking at 3.5 μm, but range from 1 to 16 mm² for the detector peaking at 4 μm. The long rise time of 1000 nsec may cause a severe loss of sensitivity as the detector cannot respond significantly to the laser pulse.

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (=A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c} = \frac{1}{4nt_s}$$

where t_s is the pulse duration. The number of pulses to be sampled is a variable that can be used to increase the SNR.

7.2.3.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by DAS is given by

$$SNR = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2 + (1/P_2)^2 + (1/P_2')^2}}$$

where

$$\begin{aligned}
 \ln Q^1 &= \ln \frac{P_1 P'_2}{P'_1 P_2} \\
 P_1 &= (G/R^2) e^{-2k_1 C R} \\
 P'_1 &= (G/(R + \Delta R)^2) e^{-2k_1 C (R + \Delta R)} \\
 P_2 &= (G/R^2) e^{-2k_2 C R} \\
 P'_2 &= (G/(R + \Delta R)^2) e^{-2k_2 C (R + \Delta R)} \\
 G &= \eta P_t \Delta R N(R) \beta A_o \\
 dP &= NEP/F = (A_d \Delta f)^{1/2} (D^*)^{-1/F} = \left(\frac{A_d}{4n t_s} \right)^{1/2} (D^*)^{-1/F} \\
 F &= 1
 \end{aligned}$$

The SNR may be simplified, i. e.,

$$SNR = \frac{Q P_{eff}}{2 NEP/F}$$

where

$$\begin{aligned}
 Q &= 2(k_1 C_1 - k_2 C_2) \Delta R \\
 P_{eff} &= G \xi(R) \\
 \xi(R) &= R^{-2} e^{-2kCR}
 \end{aligned}$$

In the following a stepwise description for the calculation of SNR is given

Step 1:

Calculate: NEP/F

Assume: $D^* = 3 \times 10^9 \text{ cm Hz}^{1/2} \text{ W}^{-1}$

$$F = 1$$

$$t_s = 1000 \text{ nsec}$$

Result: Plot in Figure 7. 2. 3-2 shows NEP/F versus A_d for different number of pulses n . It should be noted that the values for NEP/F are down by 3 orders of magnitude when compared with the LWIR region.

Step 2:

Calculate: G

Assume: $N(R)\beta \approx 8 \times 10^{-8} \text{ cm}^{-1} \text{ ster}^{-1}$

$$\Delta R = 1500 \text{ cm}$$

$P_t = 2 \times 10^4 \text{ W}$ for a $2 \times 10^{-3} \text{ J}$ laser, having a 10 cm^2 beam area and a pulse duration of 100 nsec

Result: Plot in Figure 7. 2. 3-3 shows G versus receiver aperture area A_o for three values of overall efficiency (optical and mechanical shutters)

Step 3:

Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 2. 3-4 shows $\xi(R)$ versus R for the above values of kC

Step 4:

Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7. 2. 3-5 which shows P_{eff} vs. $\xi(R)$ for different values of G .

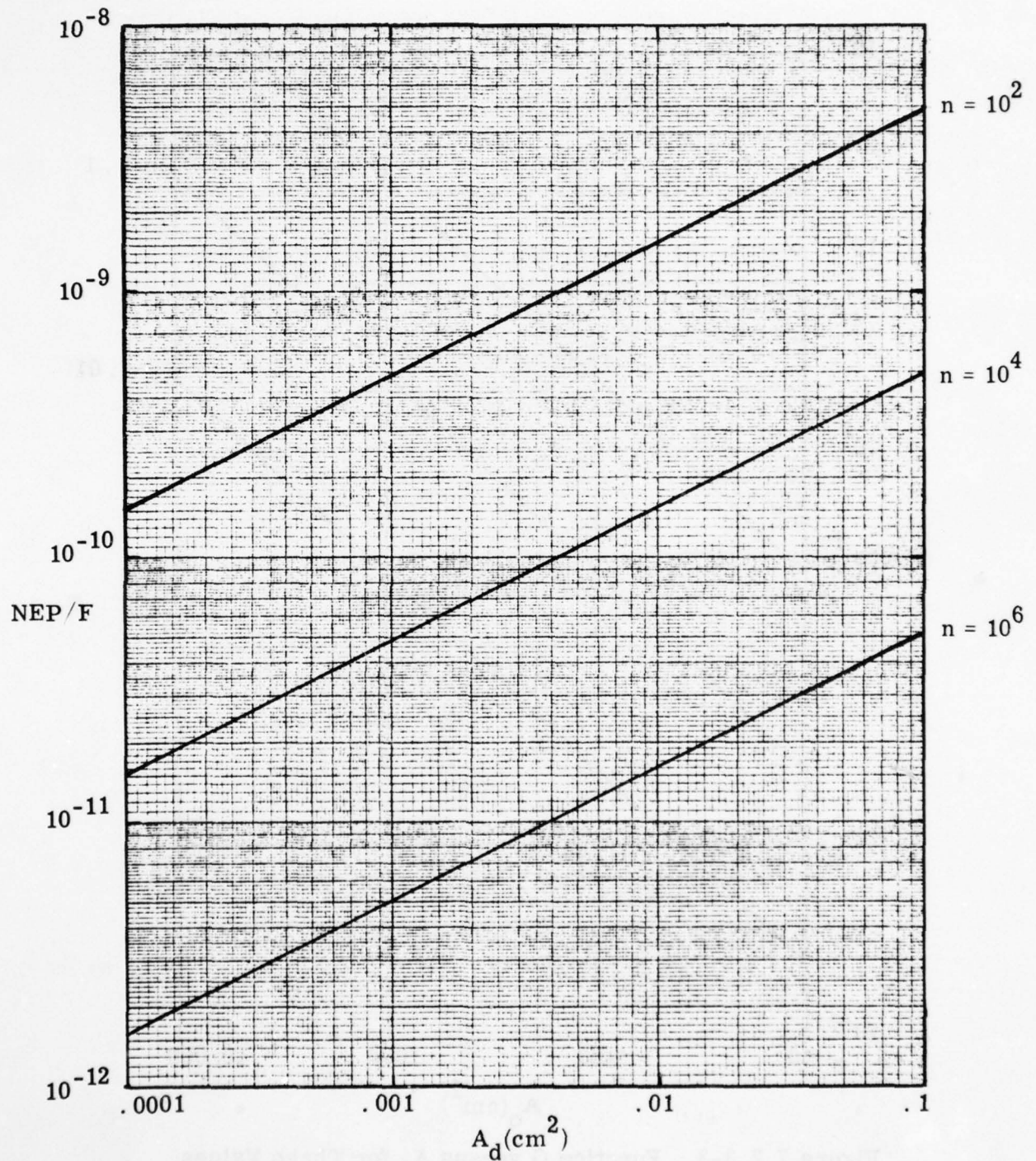


Figure 7. 2. 3-2. NEP versus A_d for Different Values of Number of Pulses, Assuming $D^* = 3 \times 10^9 \text{ cmH}^{1/2} \text{ W}^{-1}$ and $t_s = 1000 \text{ ns}$.

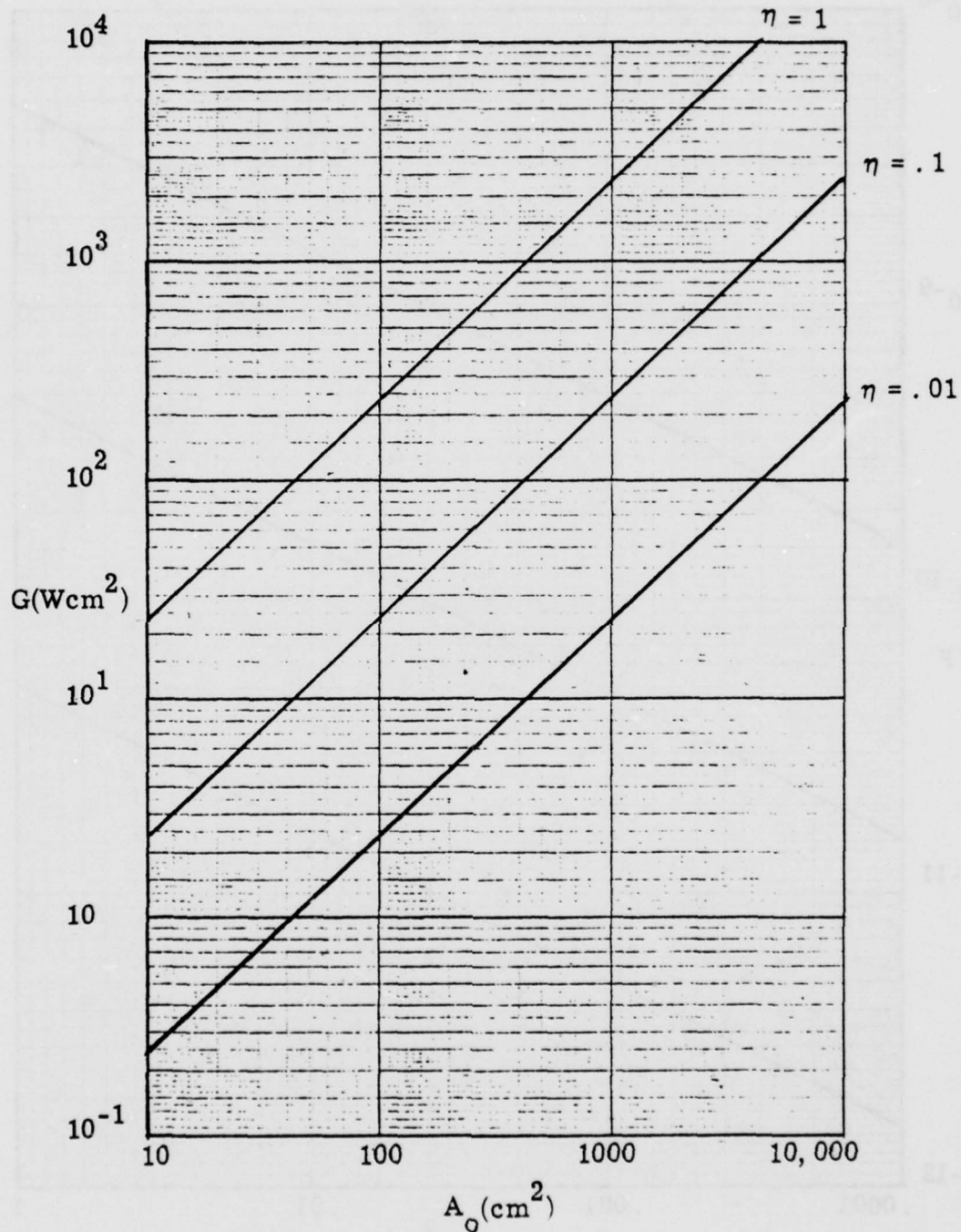


Figure 7. 2. 3-3. Function G versus A_0 for Three Values of η , using $\Delta R = 15 \text{ m}$, $N(R)\beta = 8 \times 10^{-8} \text{ cm}^{-1}\text{ster}^{-1}$ and $P_t = 2 \times 10^{-3} \text{ J}$ for 10 cm^2 laser beam area.

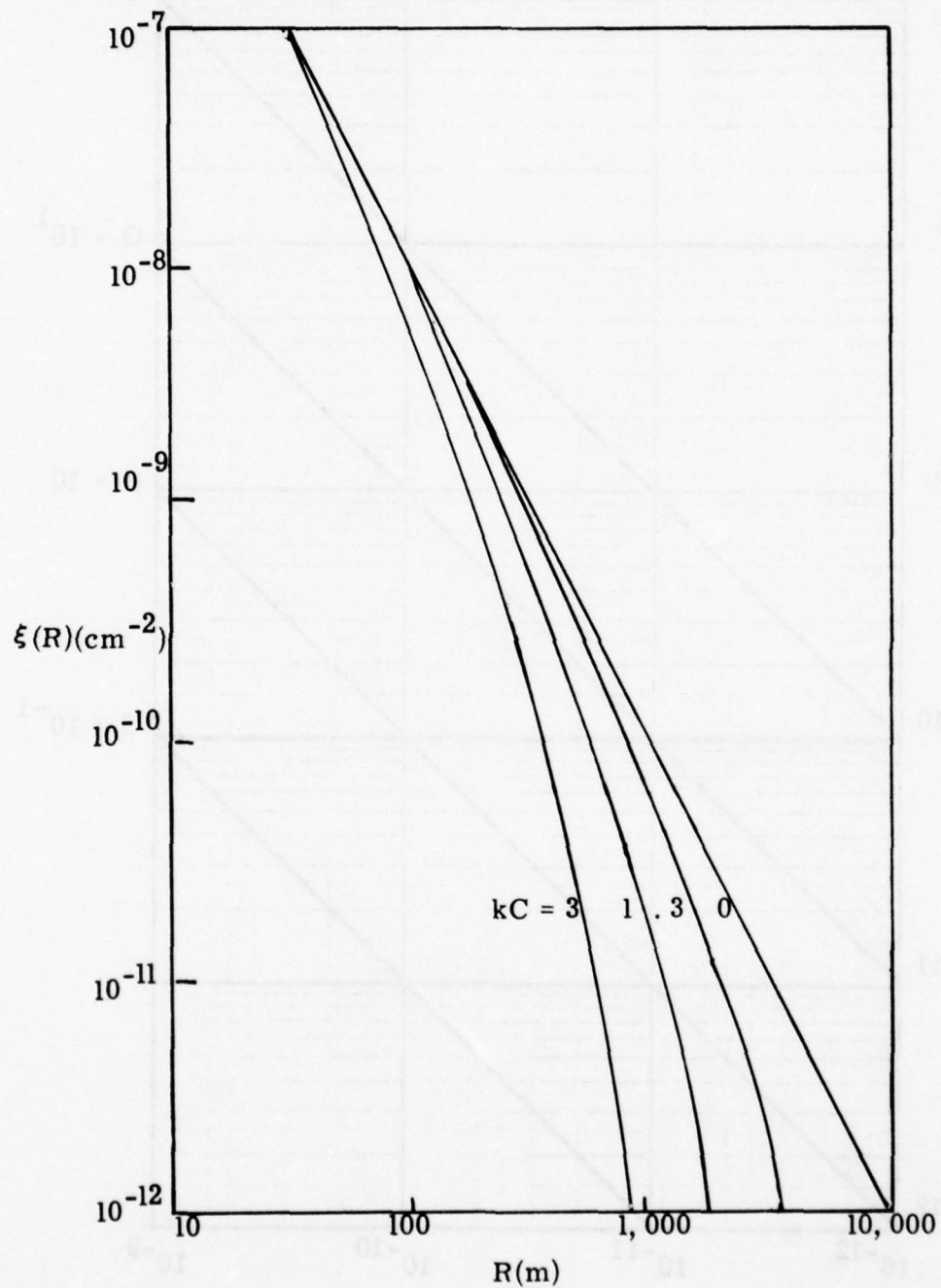


Figure 7. 2. 3-4. Function $\xi(R)$ vs. Range for Difference Values of $kC(\text{km}^{-1})$

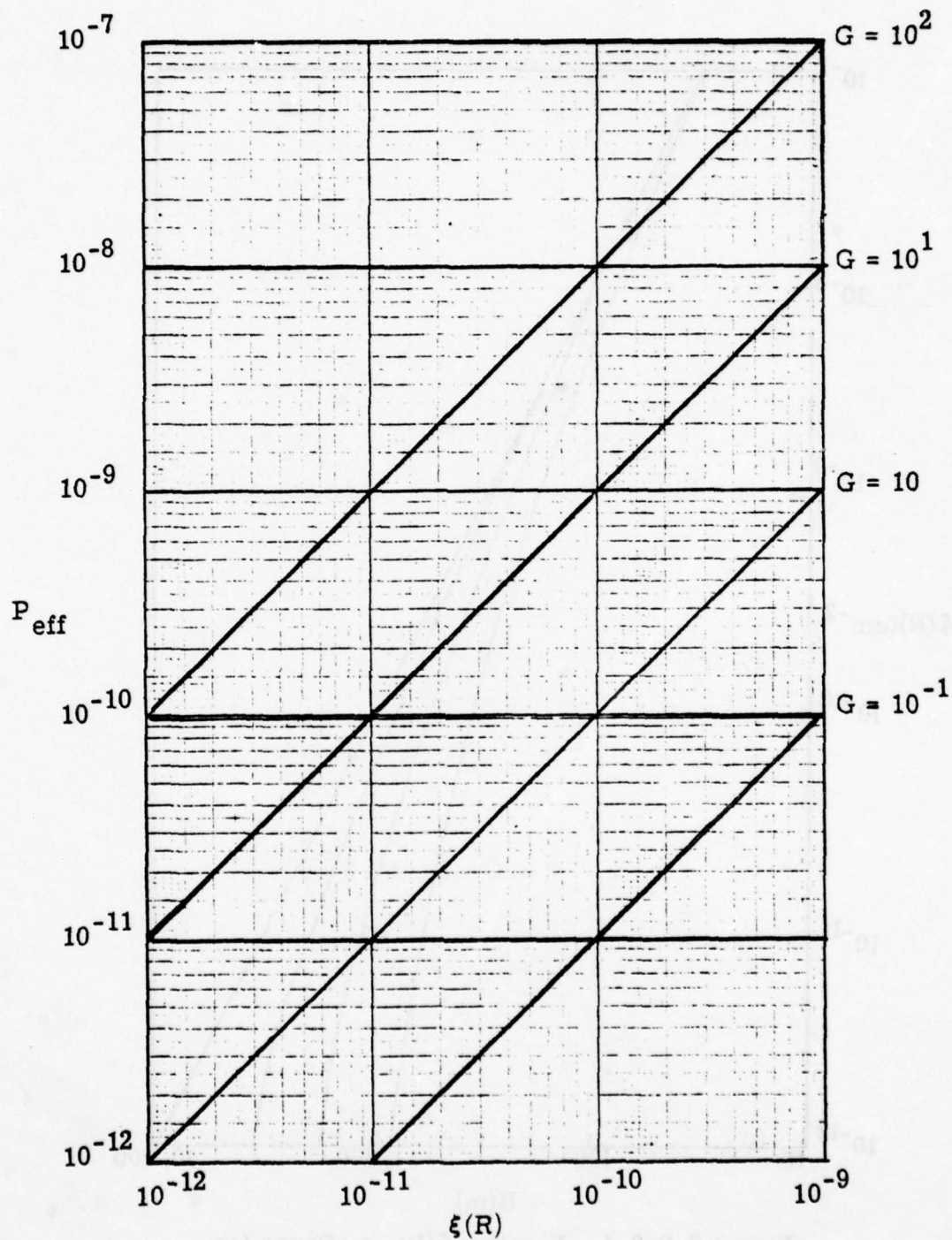


Figure 7. 2. 3-5. P_{eff} vs. the Function $\xi(R)$ for Different Values of G

Step 5: Calculate: Q for (a) NO_x , and (b) SO_2 and (c) hydrocarbons
Assume: $\Delta R = 0.015 \text{ km}$

Absorption coefficients of NO_x , SO_2 and hydrocarbons for specific laser lines have not been determined yet. Calculation cannot be completed until these values are available.

Step 6: Calculate: System Performance for $\text{SNR} = 1$, i. e., $P_{\text{eff}} = \frac{2 \text{ NEP}/F}{Q}$

- i) Determine NEP/F (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7.2.3-6)
- iii) Locate intersection between NEP/F and Q in Figure 7.2.3-7 and determine P_{eff} . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7.2.3-3.
- v) Find intersection between G and P_{eff} in Figure 7.2.3-6 and determine $\xi(R)$.
- vi) Find distance R in Figure 7.2.3-4 for a given kC .
The value of kC may be estimated by dividing 0.015 into Q , because $Q \approx kC\Delta R$ and $\Delta R = 0.015 \text{ km}$.

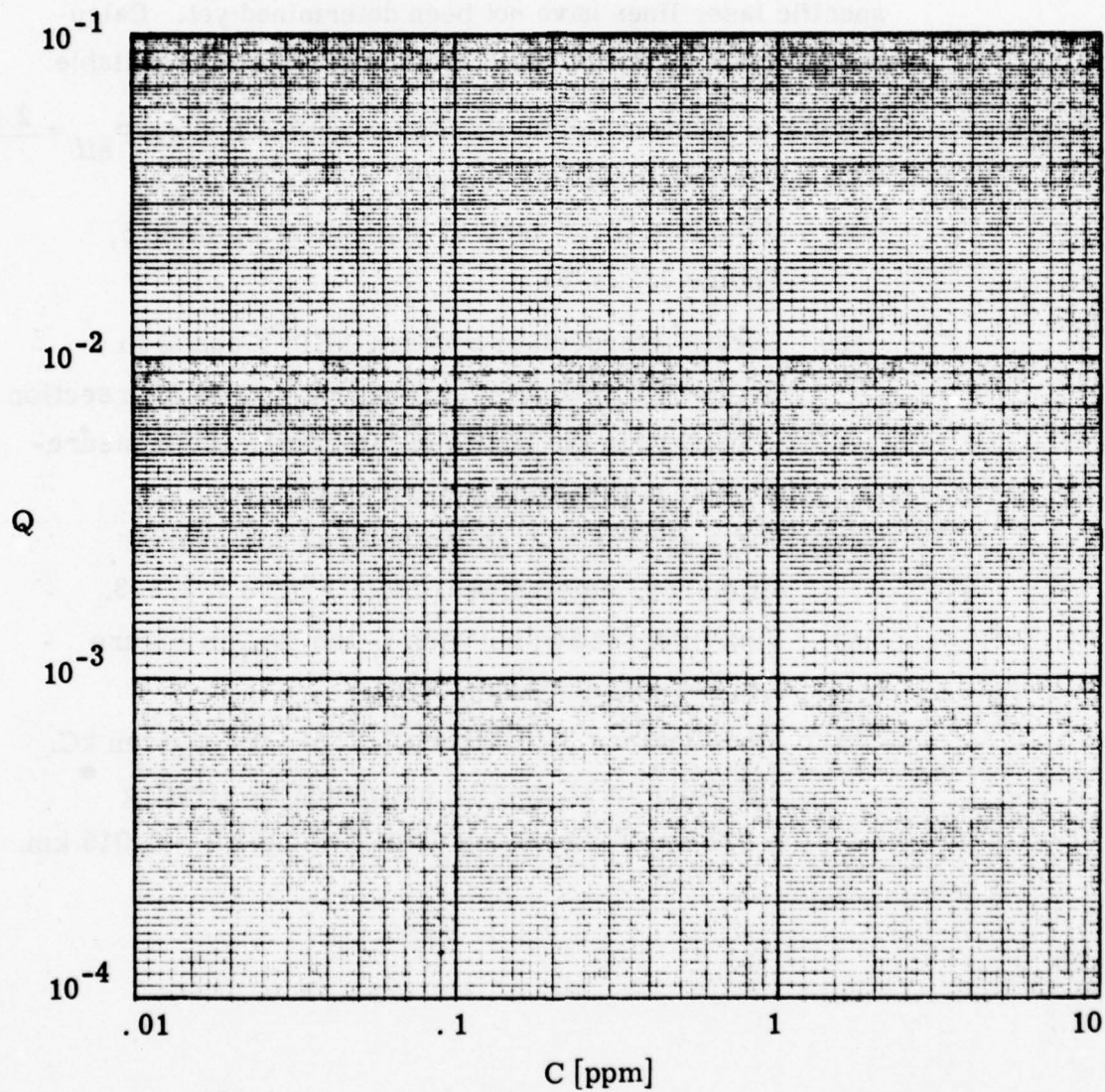


Figure 7. 2. 3-6. Q versus Concentration of NO_x , SO_2 and $\langle \text{HC} \rangle$ for a Resolution Element of 15 m. See Step 5, absorption coefficients required for this graph are not yet determined.

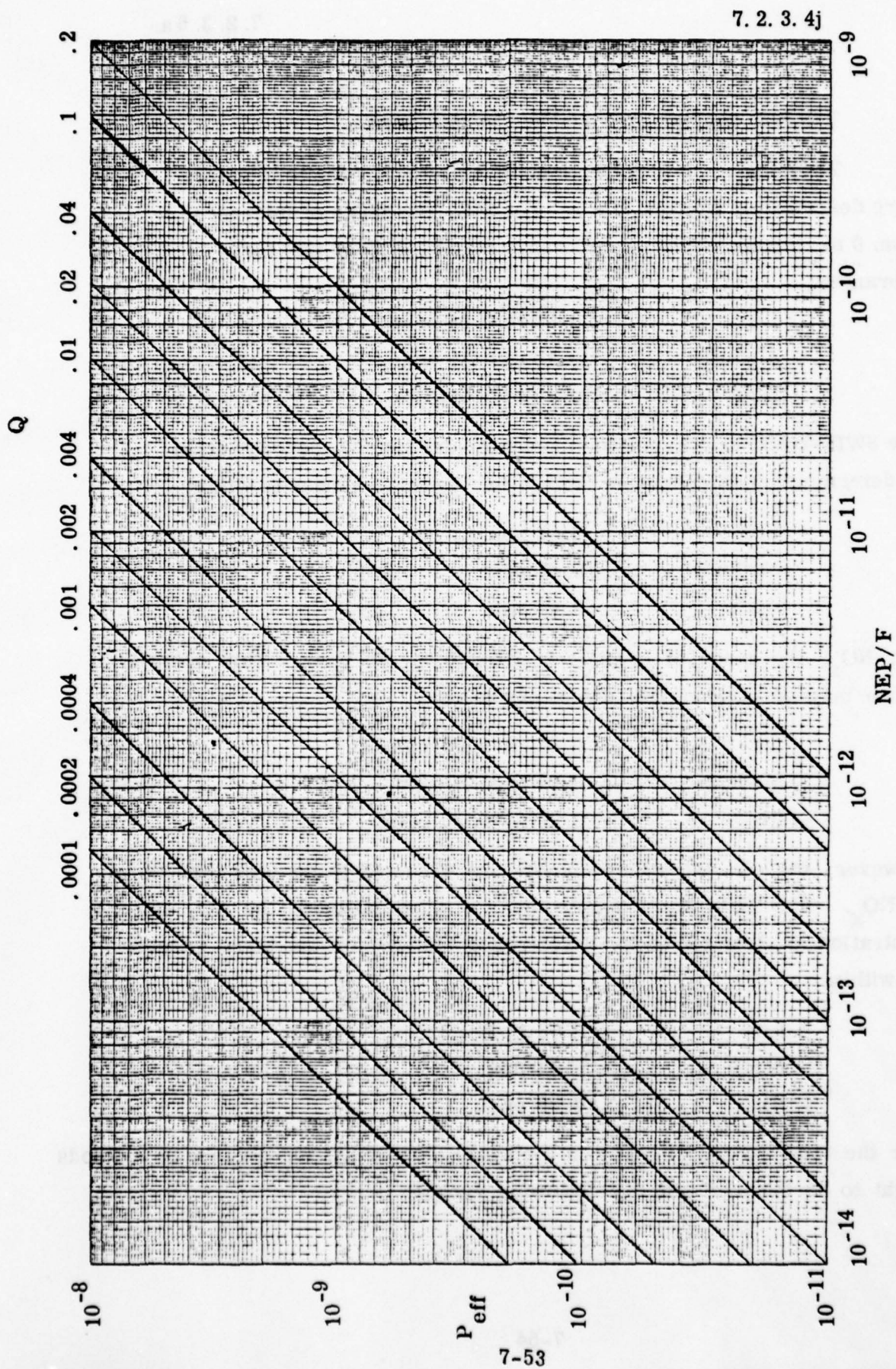


Figure 7.2.3.-7. P_{eff} versus NEP/F for Different Values of Q .

7. 2. 3. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. For SO_2 , the range of interest is from 0 to . 5 ppm. This overall range may be divided into three subranges:

Low	0. 02 to 0. 05 ppm
Medium	0. 10 to 0. 15 ppm
High	0. 40 to 0. 50 ppm

The SWIR-DAS remote monitor must measure the SO_2 concentration as determined by a reference method for the three ranges to within

Low	0. 02 ppm
Medium	0. 03 ppm
High	0. 04 ppm

For NO_x , the range of interest is from 0 to . 35 ppm. This overall range may be divided into three subranges:

Low	0. 02 to 0. 08 ppm
Medium	0. 10 to 0. 20 ppm
High	0. 25 to 0. 35 ppm

However, the concentrations for NO are expected to be less than those of NO_x . The SWIR-DAS remote monitor must measure the NO_x concentration as determined by a reference method for the three ranges to within

Low	0. 02 ppm
Medium	0. 02 ppm
High	0. 03 ppm

For the total hydrocarbons (non-methane), the range for automated methods ought to be 2 ppm, with the following ranges

7, 2. 3. 5b
7. 2. 3. 6a

Low	. 2 - . 28 ppm
Medium	. 5 - . 6 ppm
High	1 - 2 ppm

In general, however, the concentration of ethylene will appreciably be less than those for the total hydrocarbons/non-methane concentrations.

7. 2. 3. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Figure 7.2.3-8 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams as a function of range. The four signals are determined from analog signals as given in Figure 7.2.3-8. The absorption coefficients k_1 and k_2 have not been determined yet.

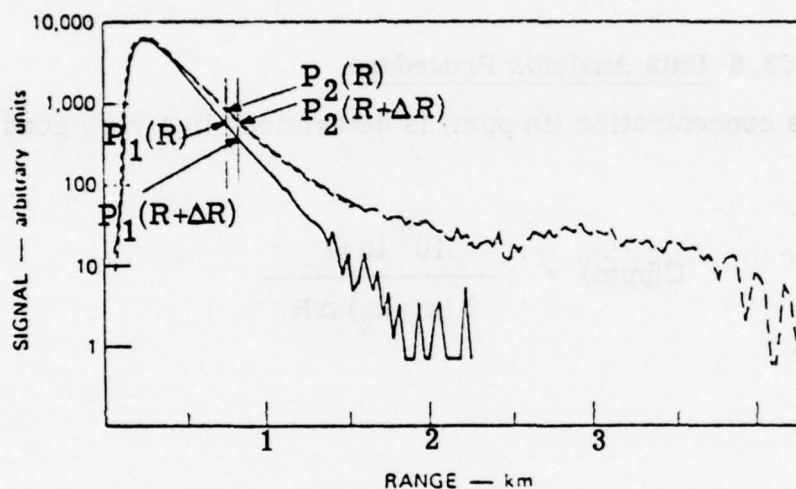


Figure 7.2.3-8. Analog Signals $P_1(R)$, $P_2(R)$, $P_1(R+\Delta R)$ and $P_2(R+\Delta R)$

7. 2. 4 UV/Visible Differential Absorption

7. 2. 4. 1 Principle of Operation

The measurement principle of ultraviolet/visible (UV/Visible) differential absorption is used to obtain range-resolved concentrations of SO₂ and NO₂. Laser pulses at two different wavelengths in the 2000-5000 Å region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the pollutants transmission can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7. 2. 4. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical UV/visible DAS system is shown in Figure 7. 2. 4. 1. It should be noted that no prototype UV/visible DAS system, using two lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR 1040.

7. 2. 4. 3 System Parameters

Commercially Available Lasers

N₂ Gas Laser

Xe Gas Laser

Neodymium Yag Solid State Laser

RDA Ruby

Dye Lasers

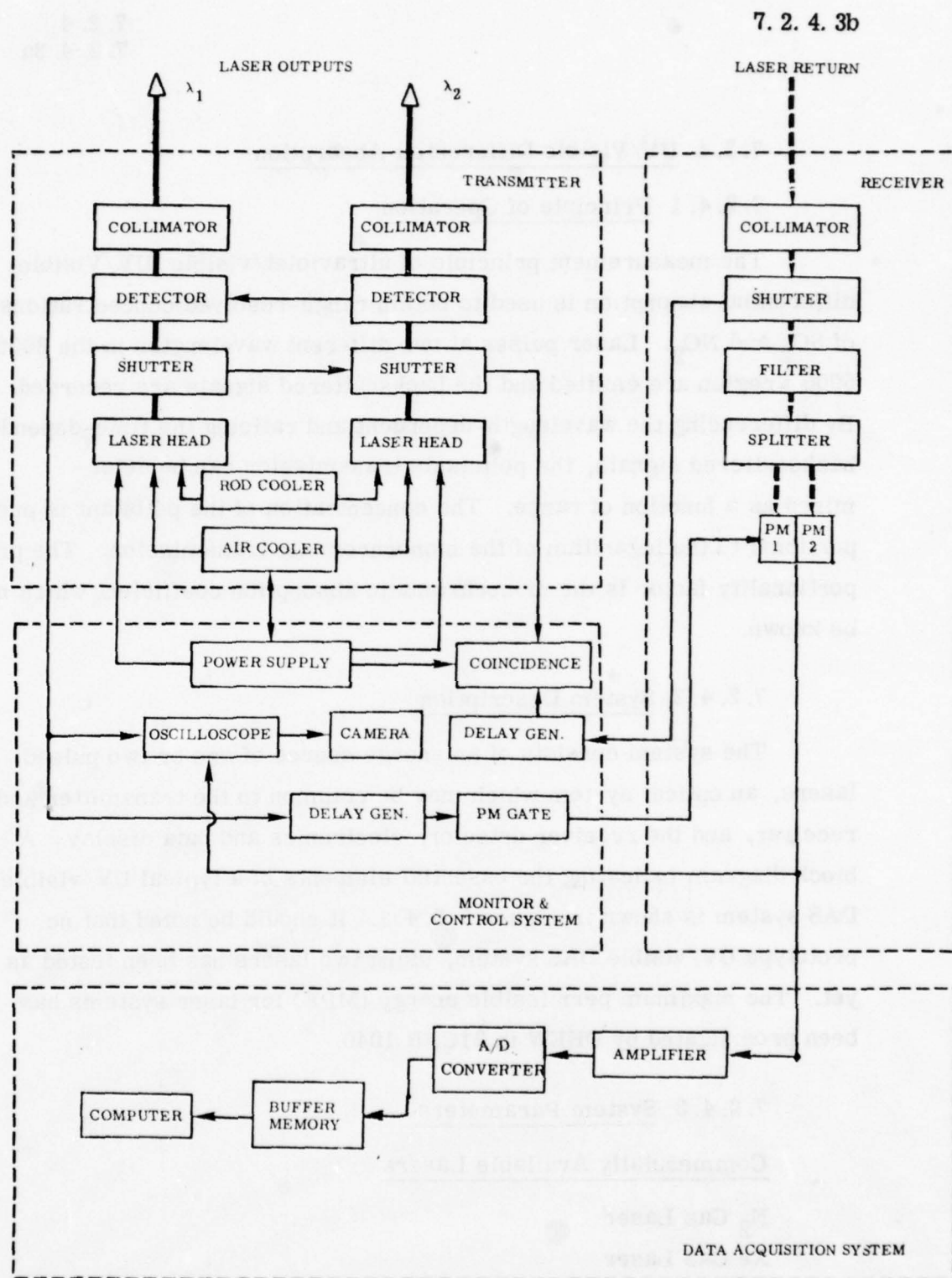


Figure 7.2.4-1. Conceptual Block Diagram of a UV/Visible DAS System (Based on Ref. 264).

Other lasers that have transitions in the UV/visible region, but are not commercially available at present, include Ar, Cl, S, Kr, Ne, F, O₂, P, B, Pb, Si, Se, In, and I. (Refs. 265 and 257).

Operational Wavelengths

Have not been determined yet.

Laser Energy

For $2500 < \lambda < 4000 \text{ \AA}$, the maximum permissible laser energy ranges from $6.2 \text{ to } 10^{-5} \text{ to } .021 \text{ J/cm}^2$ for any pulse length. In the visible spectrum, $4000 < \lambda < 7000 \text{ \AA}$, the laser energy is dependent on the pulse length, ranging from $5.2 \times 10^{-7} \text{ J/cm}^2$ for $\tau_s < 10^{-5} \text{ sec}$ to $7 \times 10^{-4} \text{ J/cm}^2$ for $t_s = 1 \text{ sec}$. These values are consistent with decreasing the laser power (W) for longer pulse durations. Shortest pulse duration of commercially available UV/visible lasers is in the nsec range. Available energy exceeds MPE by orders of magnitude.

Detector

Commercially available detectors are photomultipliers or Digicons having response curves S-13 or S-19. These tubes are very sensitive and have low noise figures. In general, the UV/visible receivers become shot and/or background noise limited.

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below)

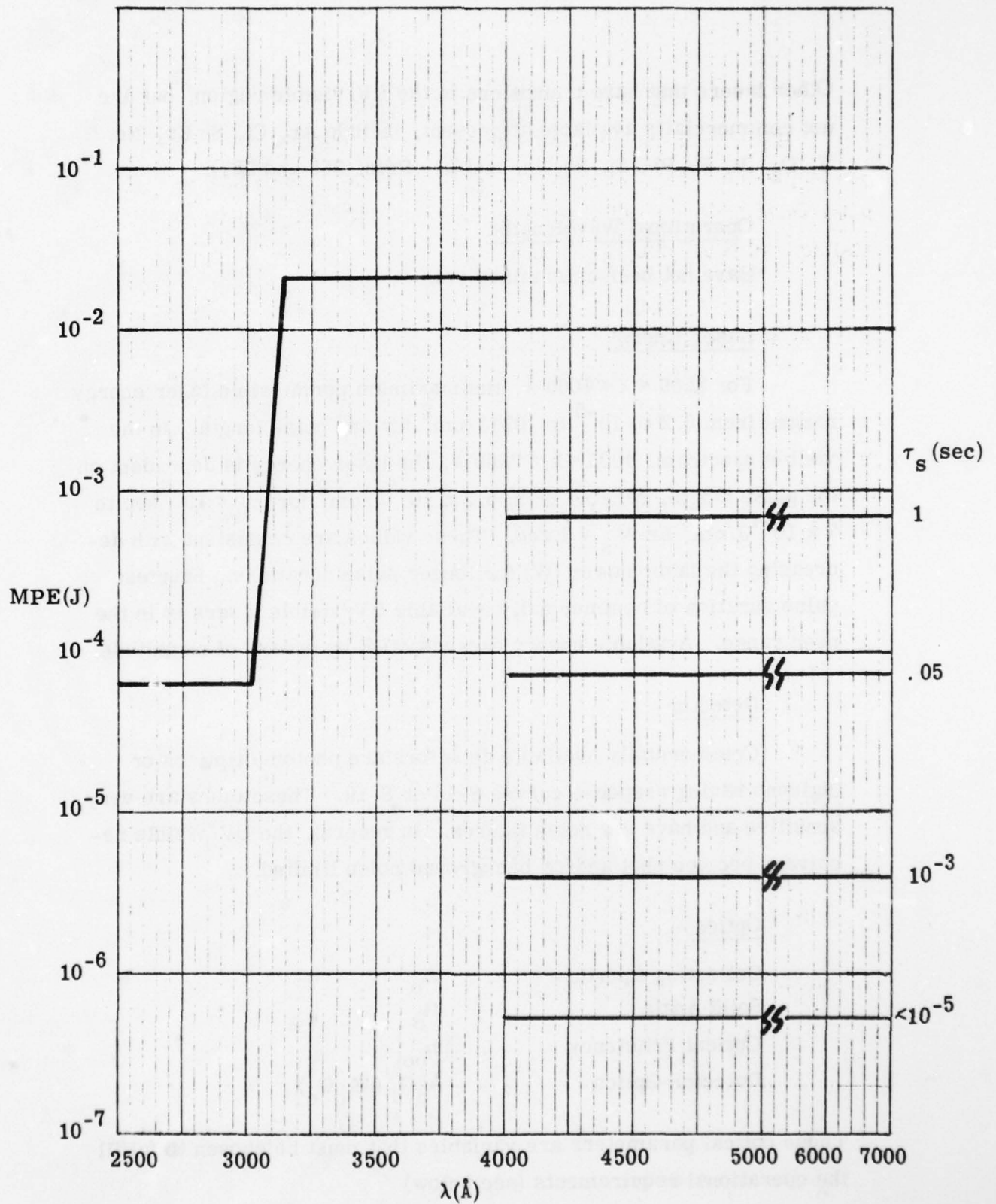


Figure 7. 2. 4-2. Maximum Permissible Laser Energy versus λ for Different Pulse Lengths

7. 2. 4. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a shot-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by UV/visible DAS is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2 + (1/P_2)^2 + (1/P_2')^2}}$$

where

$$\ln Q^1 = \ln \frac{P_1 P_2'}{P_1' P_2}$$

$$P_1 = (G/R^2) e^{-2k_1 C R}$$

$$P_1' = (G/(R + \Delta R)^2) e^{-2k_1 C (R + \Delta R)}$$

$$P_2 = (G/R^2) e^{-2k_2 C R}$$

$$P_2' = (G/(R + \Delta R)^2) e^{-2k_2 C (R + \Delta R)}$$

$$G = \eta P_t \Delta R N(R) \beta A_o$$

$$dP = (P_{\text{eff}} h\nu / \eta t_s)^{1/2}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q}{2} \left(\frac{\eta Q t_s}{h\nu} P_{\text{eff}} \right)^{1/2}$$

where

$$Q = 2(k_1 C_1 - k_2 C_2) \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: G

Assume: $N(R)\beta \approx 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$

$\Delta R = 1500 \text{ cm}$

$P_t = 2 \times 10^{-1} \text{ J}$ for $3000 - 4000 \text{ \AA}$ and $5.2 \times 10^{-6} \text{ J}$ for $4000 - 7000 \text{ \AA}$, using 10 cm^2 laser beam area and pulse duration of 10^{-7} sec .

Result: Plot in Figure 7.2.4-3 and -4 shows G versus receiver aperture area A_o for three values of overall efficiency (optical and mechanical shutters)

Step 2: Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.2.4-5 shows $\xi(R)$ versus R for the above values of kC

Step 3: Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7.2.4-6 which shows P_{eff} vs. $\xi(R)$ for different values of G .

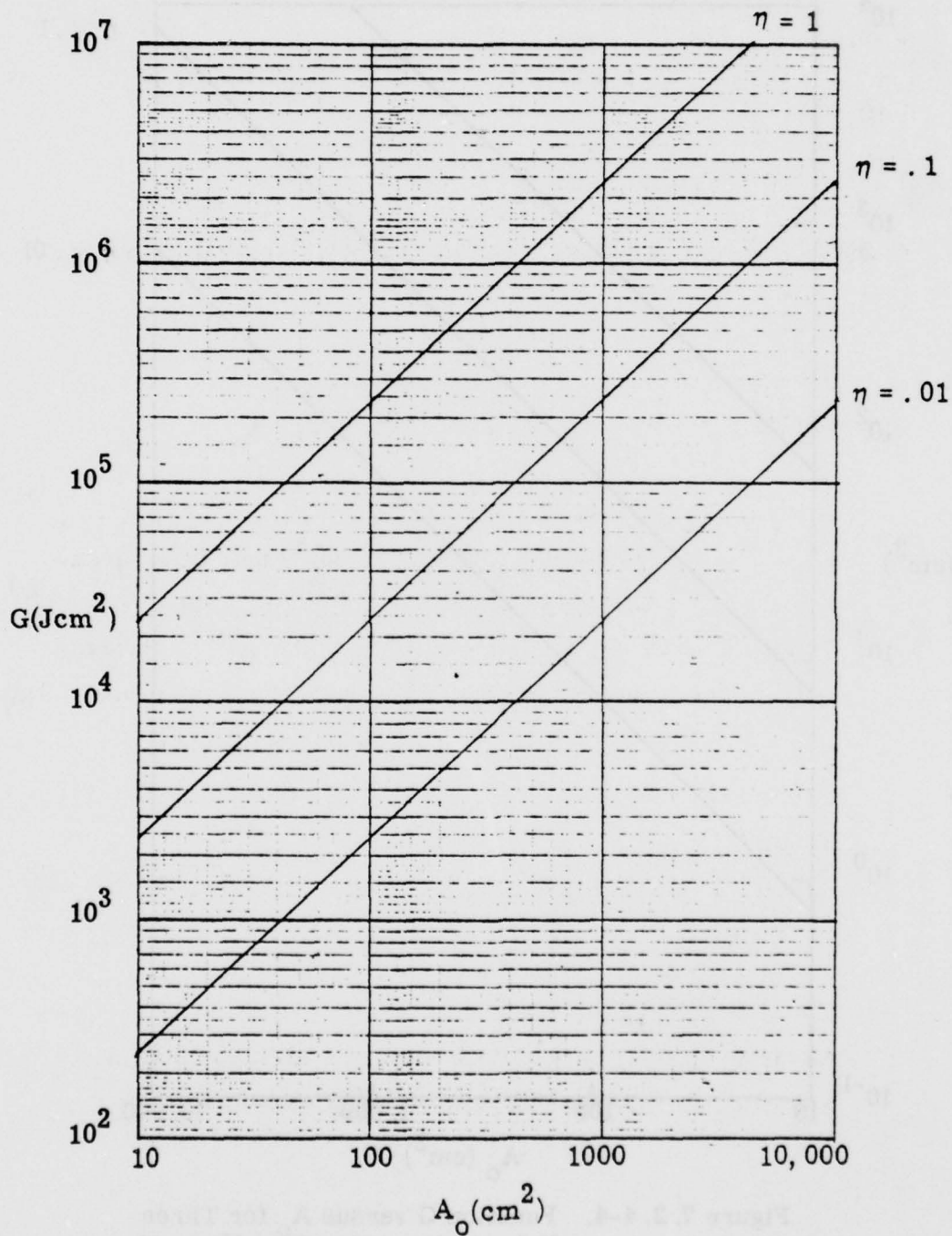


Figure 7. 2. 4-3. Function G versus A_0 for Three Values of η , using $\Delta R = 15$ m, $N(R)\beta = 8 \times 10^{-7}$ $\text{cm}^{-1}\text{ster}^{-1}$ and $P_t = 2 \times 10^{-1}$ J for 10 cm^2 laser beam area, useful in range 3000-4000 Å.

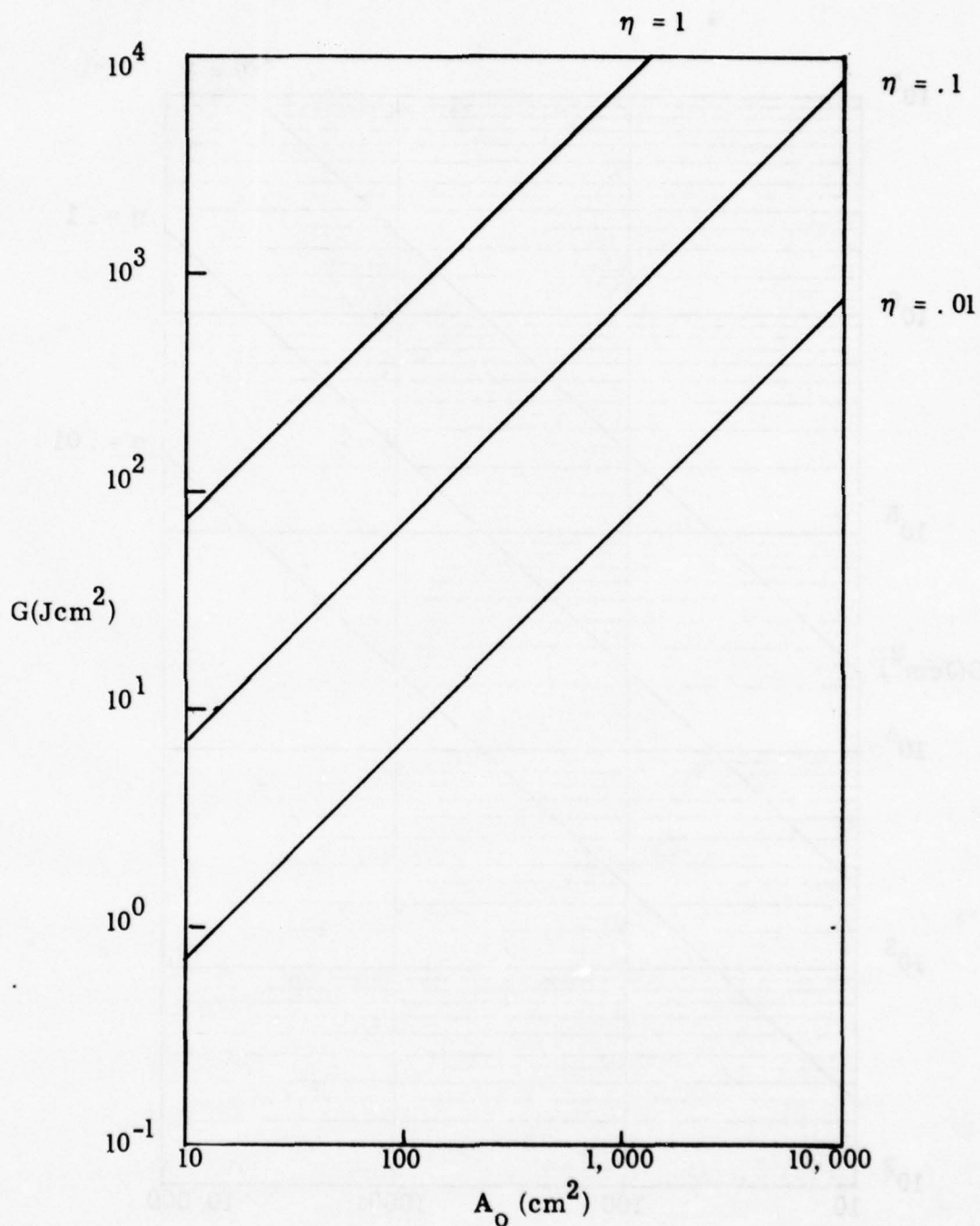


Figure 7. 2. 4-4. Function G versus A_0 for Three Values of η , using $\Delta R = 15 \text{ m}$, $N(R)\beta = 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$ and $P_t = 5.2 \times 10^{-6} \text{ J}$ for 10 cm^2 laser beam area, useful in the visible region from 4000 to 7000 \AA .

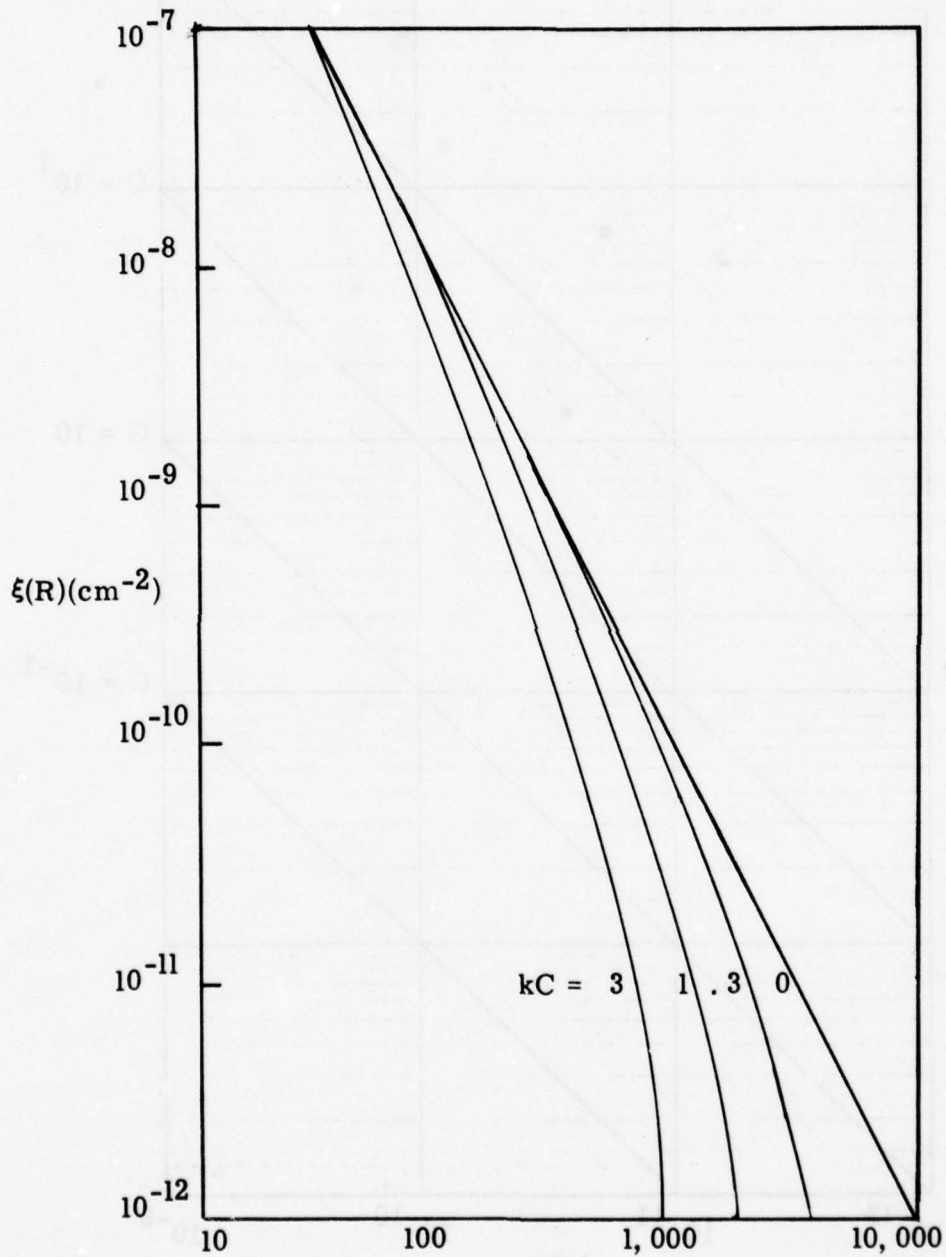


Figure 7.2.4-5. Function $\xi(R)$ vs. Range for Different Values of $kC(\text{km}^{-1})$

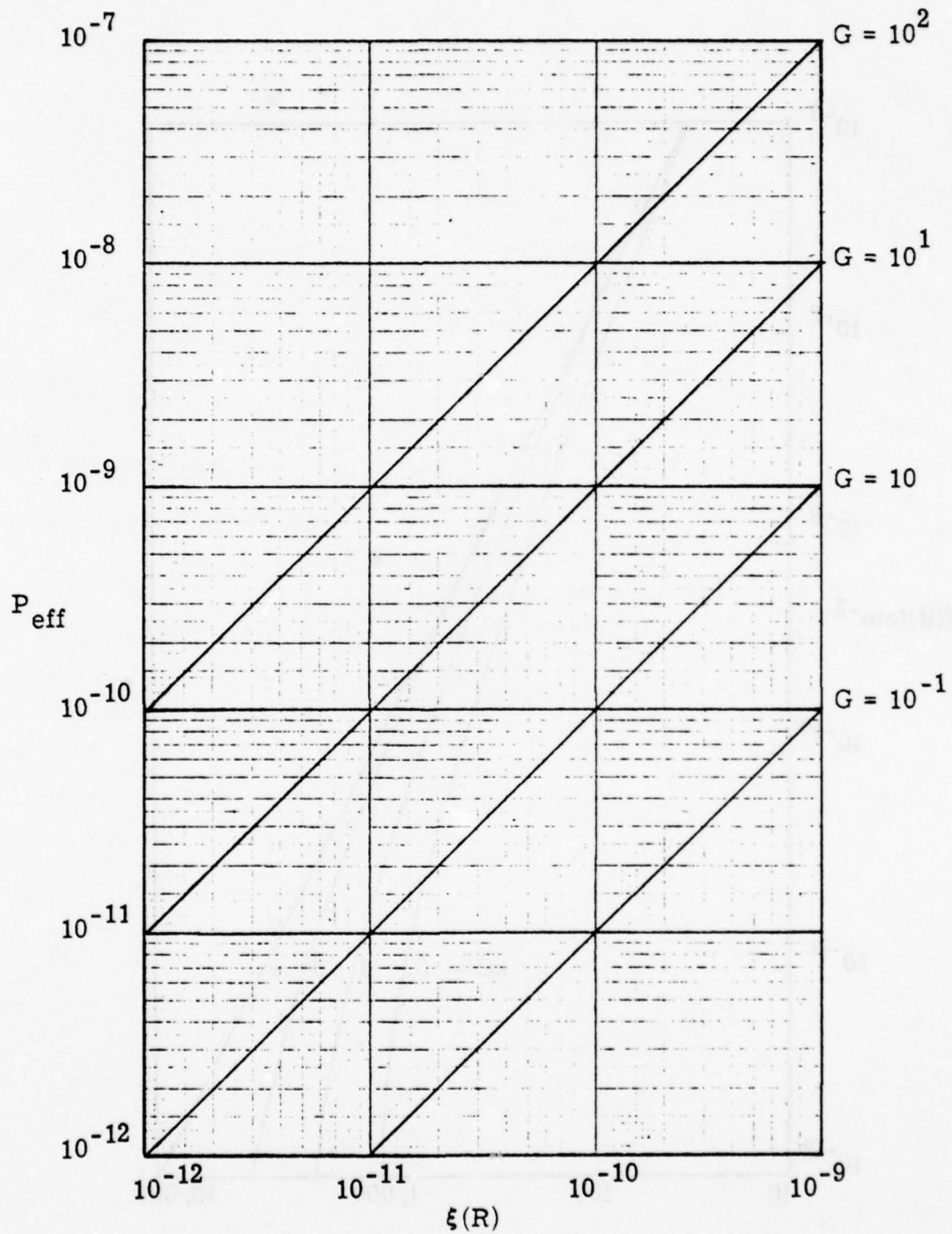


Figure 7. 2. 4-6. P_{eff} vs. the Function $\xi(R)$ for Different Values of G

Step 4: Calculate Q for (a) SO₂ and (b) NO₂

Assume: $\Delta R = 0.015$ km

Absorption coefficients of SO₂ and NO₂ for specific laser lines have not been determined yet. Calculation cannot be completed until these values are available.

Result: Q versus C to be plotted in Figure 7. 2. 4 -7.

Step 5: Calculate: System Performance for NSR = 1, i. e. ,

$$P_{\text{eff}} = \frac{h\nu}{\eta \text{ tg}} \frac{4}{Q^2}$$

- (i) Calculate Q for desired concentration (Step 4, Figure 7. 2. 4-7)
- (ii) Locate intersection between λ and Q in Figure 7. 2. 4 -8 and determine P_{eff}
- (iii) For a given receiver optics area and overall efficiency, determine G from Figure 7. 2. 4-3 or 4.
- (iv) Find intersection between G and P_{eff} in Figure 7. 2. 4-8 and determine $\xi(R)$.
- (v) Find the distance R in Figure 7. 2. 4-5 for a given kC. The value of kC may be estimated by dividing 0.015 into Q, because $Q \approx R \Delta R$ and $\Delta R = 0.015$ km.

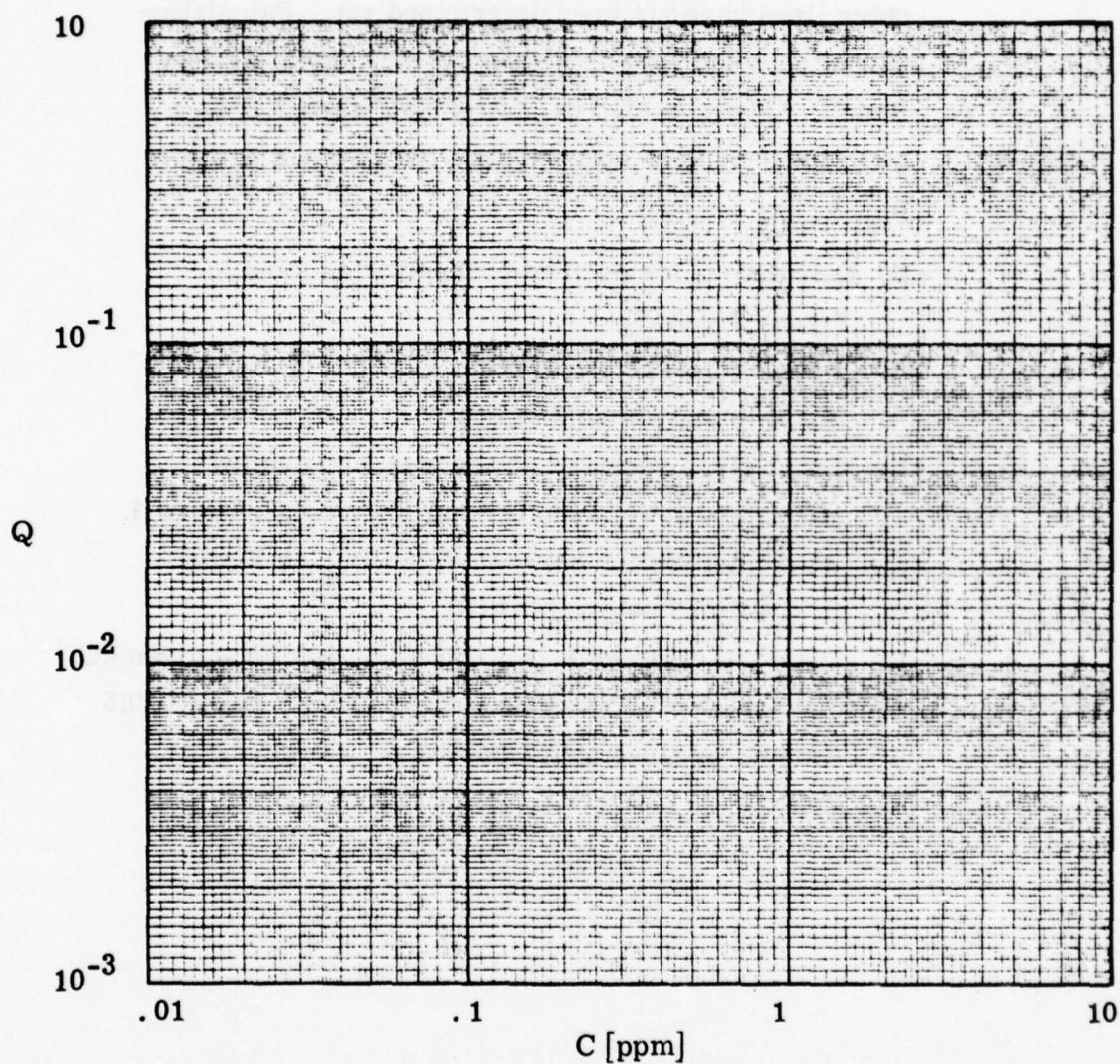


Figure 7. 2. 4-7. Q versus Concentration of SO_2 and NO_2 for a Resolution Element of 15 m. See Step 4, absorption coefficients required for this graph are not yet determined.

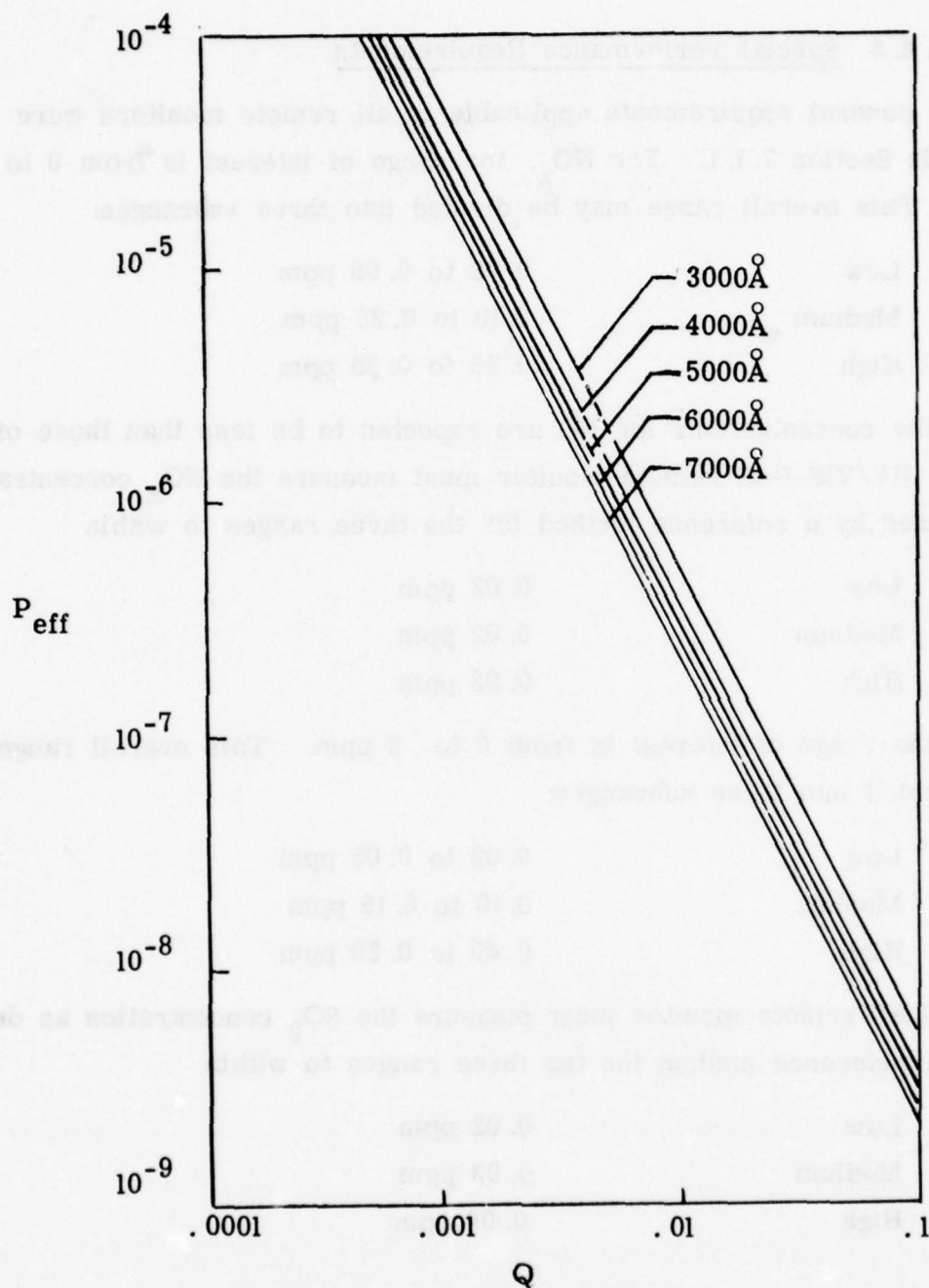


Figure 7.2.4-8. P_{eff} versus Q for $3000 < \lambda < 7000 \text{ \AA}$.

7. 2. 4. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For NO_x , the range of interest is from 0 to .35 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.08 ppm
Medium	0.10 to 0.20 ppm
High	0.25 to 0.35 ppm

However, the concentrations for NO are expected to be less than those of NO_x . The UV/VIS-DAS remote monitor must measure the NO_x concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.02 ppm
High	0.03 ppm

For SO_2 , the range of interest is from 0 to .5 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.05 ppm
Medium	0.10 to 0.15 ppm
High	0.40 to 0.50 ppm

The SWIR-DAS remote monitor must measure the SO_2 concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.03 ppm
High	0.04 ppm

7.2.4.6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Figure 7.2.4-9 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams as a function of range. The four signals are determined from analog signals as given in Figure 7.2.4-9. The absorption coefficients k_1 and k_2 have not been determined yet.

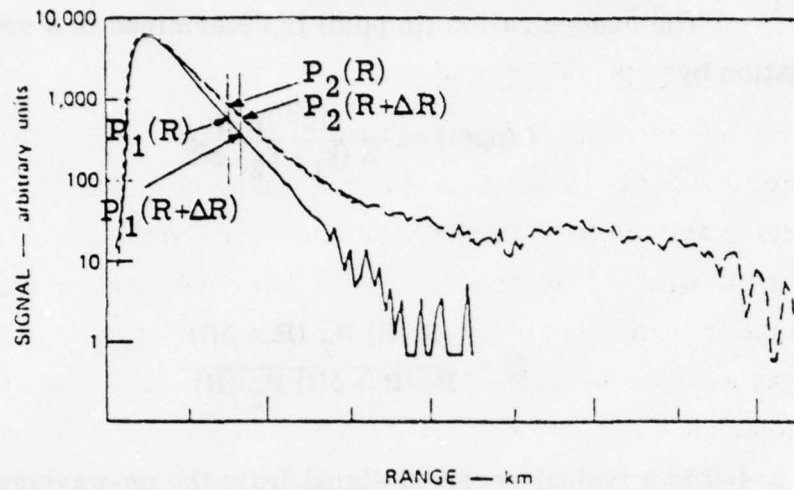


Figure 7.2.4-9. Analog Signals $P_1(R)$, $P_2(R)$, $P_1(R+\Delta R)$ and $P_2(R+\Delta R)$.

7.2.5 LIDAR

7.2.5.1 Principle of Operation

The measurement principle of Lidar is used to obtain range-resolved opacities due to particulate matter. Laser pulses in the visible spectrum are emitted and the backscattered signals are recorded. By ratioing the time-dependent backscattered signals, the particulate matter transmission can be determined as a function of range. The concentration of the particles is proportional to the logarithm of the transmission. The proportionality factor is the extinction coefficient which must be known. Since the NAAQS is given in terms of mass density, relationships between opacity and mass density for different particles must first be established. Tentative relationships have been proposed as discussed in the Lidar section (in particular, Section 5.2.1.1).

7.2.5.2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system (Figure 7.2.5-1) is basically the same as for UV/VIS DAS, except that only one wavelength instead of two is required. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040.

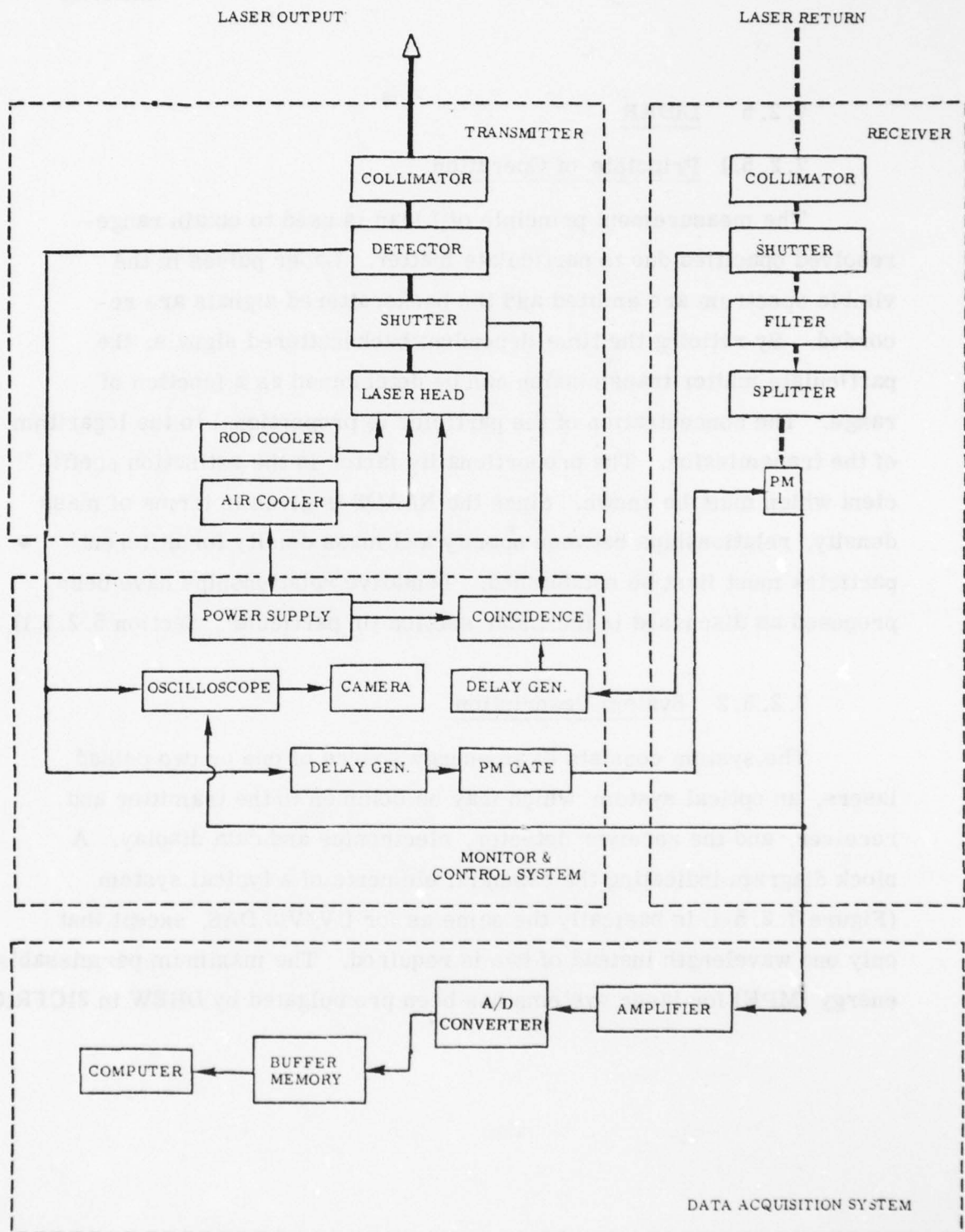


Figure 7. 2. 5-1. Conceptual Block Diagram of a LIDAR System
(Based on Ref. 264).

7. 2. 5. 3 System ParametersCommercially Available Lasers

Ar Gas Laser
 Ar/Kr Gas Laser
 Ne Gas Laser
 Kr Gas Laser
 Xe Gas Laser
 Neodymium Yag Solid State Laser
 Ruby Solid State Laser
 Dye Laser

Operational Wavelengths

<u>Laser</u>	<u>$\lambda(\text{\AA})$</u>	<u>$P_{\max}(\text{J})$</u>	<u>$\tau_s(\text{ns})$</u>
Ar	4579-5395	10^{-4}	6000
Ar/Kr	4580-6470	10^{-6}	15
Kr	4762-6764	6×10^{-5}	40
Ne	5401	3×10^{-5}	3
Xe	3645-5395	10^{-4}	500
Neod-Yag	5320	4×10^{-2}	15
Ruby	6943	1	150

Potential interfering atmospheric lines are listed in Refs. 265 and 266.

Laser Energy

$5.2 \times 10^{-7} \text{ J/cm}^2$ for pulses $< 10^{-5} \text{ sec.}$

Shortest pulse duration of commercially available CO_2 lasers is in the nsec range. Available energy exceeds MPE by orders of magnitude.

Detector

Commercially available detectors are photomultipliers or Digicons having the response curve S-19. These tubes are very sensitive and have low noise figures. In general, the UV/visible receivers become shot or background noise limited.

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (=A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below).

7. 2. 5. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a shot-noise-limited system. The signal-to-noise ratio for the determination of the opacity due to particles is given by

$$SNR = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2}}$$

where

$$\begin{aligned} \ln Q^1 &= \ln \frac{P}{P'} \\ P &= (G/R^2) e^{-2\beta_{ext}R} \\ P' &= (G/(R + \Delta R)^2) e^{-2\beta_{ext}(R + \Delta R)} \end{aligned}$$

$$G = \eta P_t \Delta R N(R) \beta A_o$$

$$dP = (P_{\text{eff}} h\nu / \eta Q t_s)^{1/2}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q}{2} \left(\frac{\eta Q t_s}{h\nu} P_{\text{eff}} \right)^{1/2}$$

where

$$Q = 2 \beta_{\text{ext}} \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = \frac{1}{R} e^{-2\beta_{\text{ext}} R}$$

where β_{ext} is the extinction coefficient.

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: G

Assume: $N(R)\beta \approx 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$

$\Delta R = 1500 \text{ cm}$

$P_t = 5.2 \times 10^1 \text{ W}$ for 10 cm^2 laser beam area
and $4000\text{-}7000 \text{ \AA}$

Result: Plot in Figure 7. 2. 5-2 shows G versus receiver aperture area A_o for three values of overall efficiency (optical and mechanical shutters)

Step 2: Calculate: $\xi(R) = \frac{1}{R} e^{-2\beta_{\text{ext}} R}$

Assume: $\beta_{\text{ext}} = 0, .3, 1, 2 \text{ km}^{-1}$

Result: Plot in Figure 7. 2. 5-3 shows $\xi(R)$ versus R for the above values of β_{ext}

Step 3:

Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m.

Result: Plot in Figure 7. 2. 5-4 which shows P_{eff} vs. $\xi(R)$ for different values of G .

Step 4:

Calculate: Q for particulate matter

Assume: $\Delta R = 15$ km. Use approximate relationship between mass density and total extinction coefficient as outlined in Section 5. 2. 1. 1 in this report.

Result: Plot in Figure 7. 2. 5-5 shows Q for particulate matter versus mass density for $\Delta R = 15$ km. also following table, where Q is given as functions of wavelength and mass density.

λ	$\rho=10$	30	100	300	1000
4000	1.70^{-3}	3.46^{-3}	9.63^{-3}	2.73^{-2}	8.80^{-2}
4500	1.14^{-3}	2.71^{-3}	8.17^{-3}	2.38^{-2}	7.85^{-2}
5000	8.37^{-4}	2.24^{-3}	7.15^{-3}	2.12^{-2}	7.02^{-2}
5500	6.57^{-4}	1.93^{-3}	6.38^{-3}	1.91^{-2}	6.36^{-2}
6000	5.11^{-4}	1.67^{-3}	5.74^{-3}	1.74^{-2}	5.80^{-2}
6500	4.30^{-4}	1.50^{-3}	5.24^{-3}	1.59^{-2}	5.34^{-2}
7000	3.51^{-4}	1.34^{-3}	4.81^{-3}	1.47^{-2}	4.94^{-2}

Step 5:

Calculate: System Performance for $\text{SNR} = 1$, i. e., $P_{\text{eff}} = \frac{h\nu}{\eta t g} \frac{4}{Q^2}$

- Calculate Q for desired mass density and wavelength (Step 4, Figure 7. 2. 5-5)
- Locate intersection between λ and Q in Figure 7. 2. 5-6 and determine P_{eff} . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.

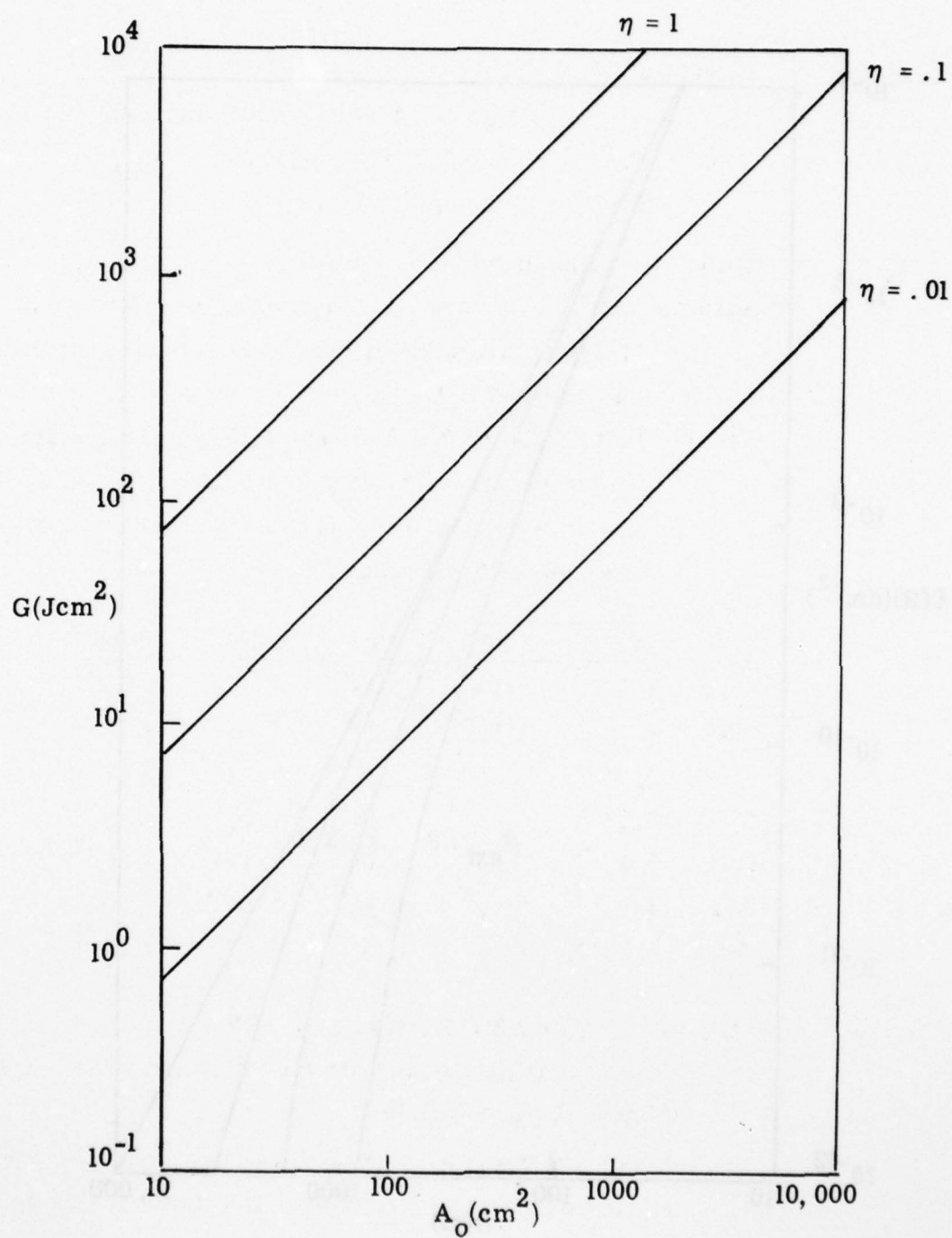


Figure 7. 2. 5-2 Function G versus A_0 for Three Values of η , using $\Delta R = 15 \text{ m}$, $N(R)\beta = 8 \times 10^{-7} \text{ cm}^{-1}\text{ster}^{-1}$ and $P_t = 5.2 \times 10^{-5} \text{ J}$ for 10 cm^2 laser beam area, useful in the visible region from 4000 to 7000 \AA .

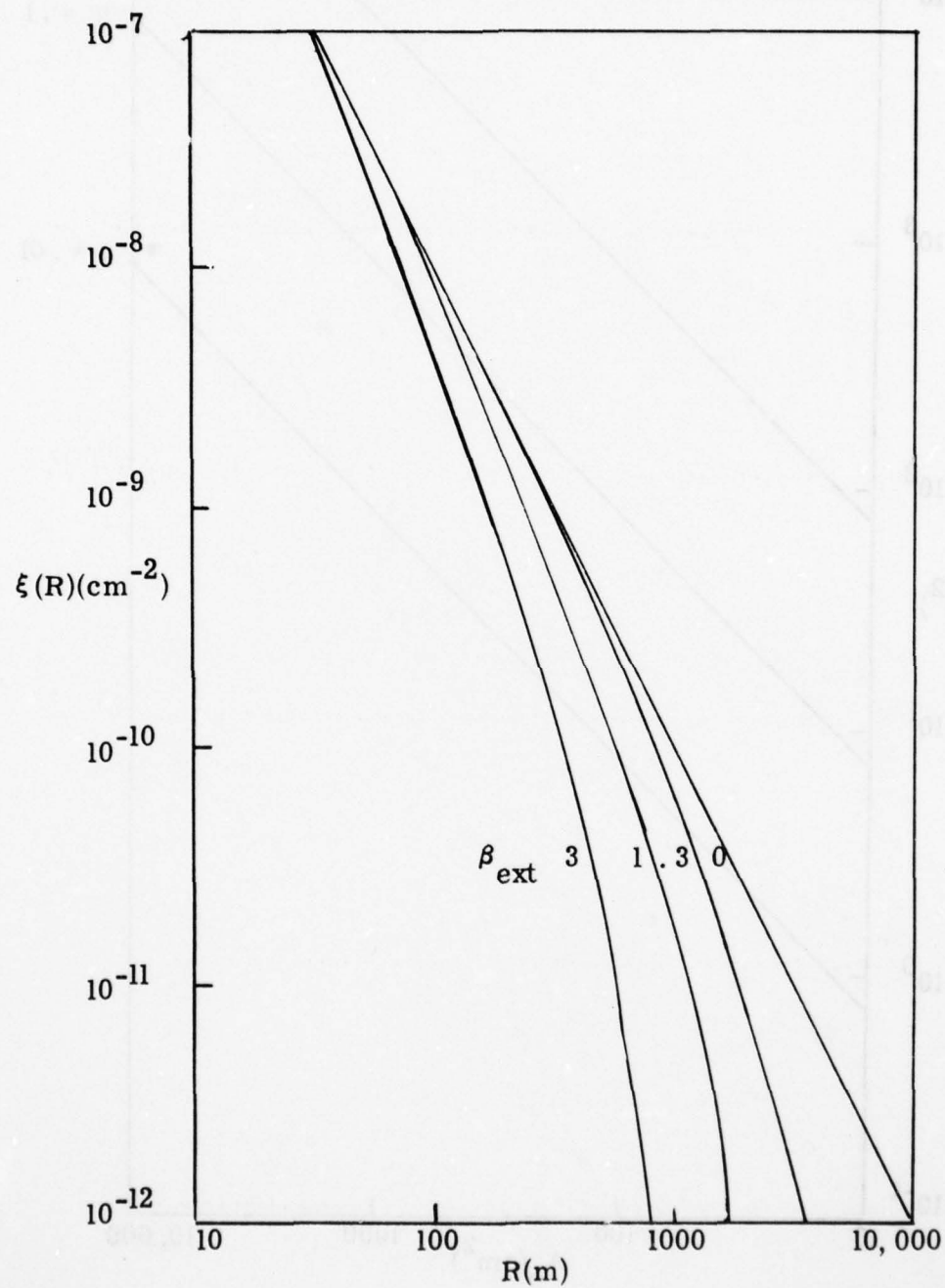


Figure 7. 2. 5-3. Function $\xi(R)$ vs. Range for Different Values of β_{ext} (km^{-1})

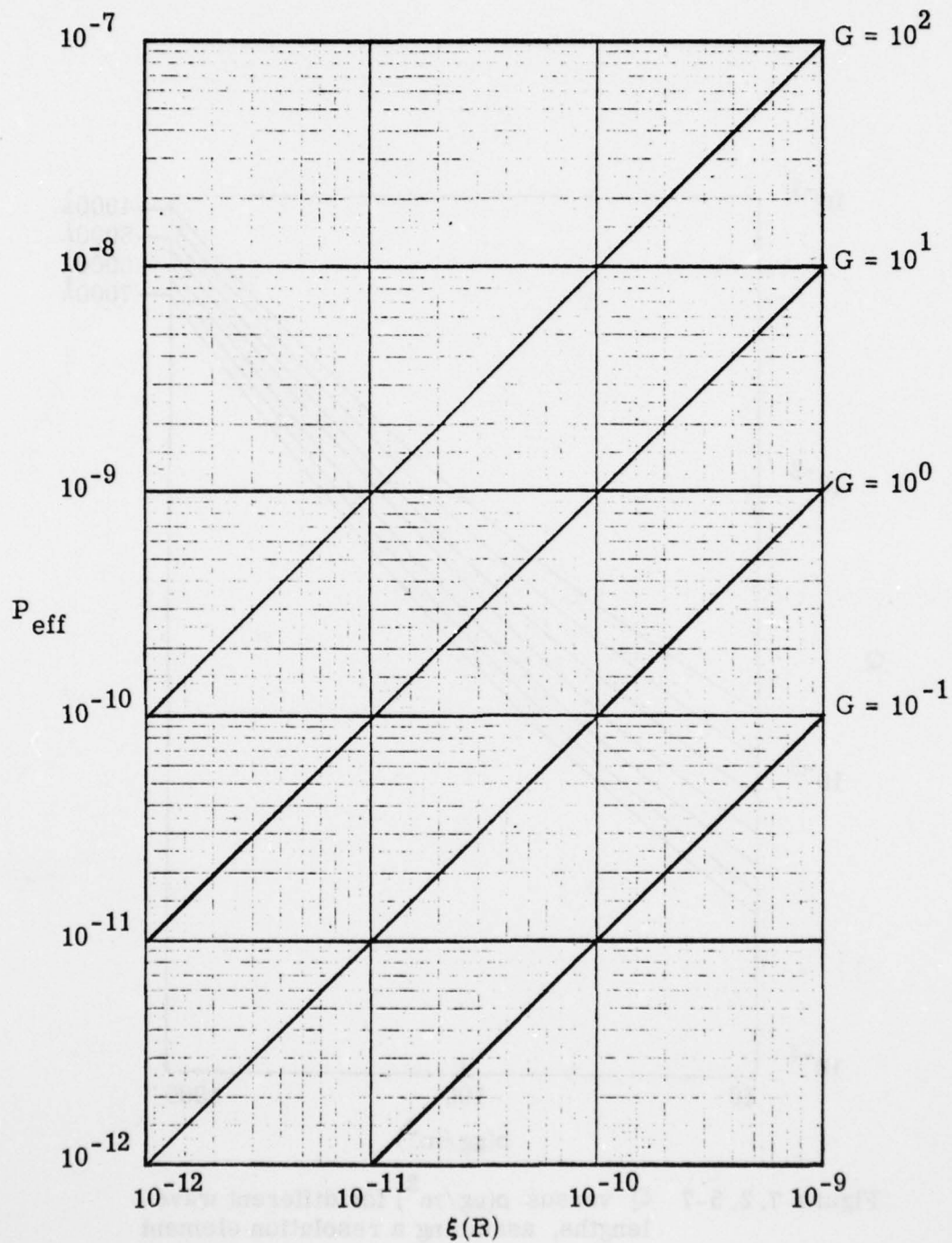


Figure 7. 2. 5 -4 P_{eff} vs. the Function $\xi(R)$ for Different Values of G

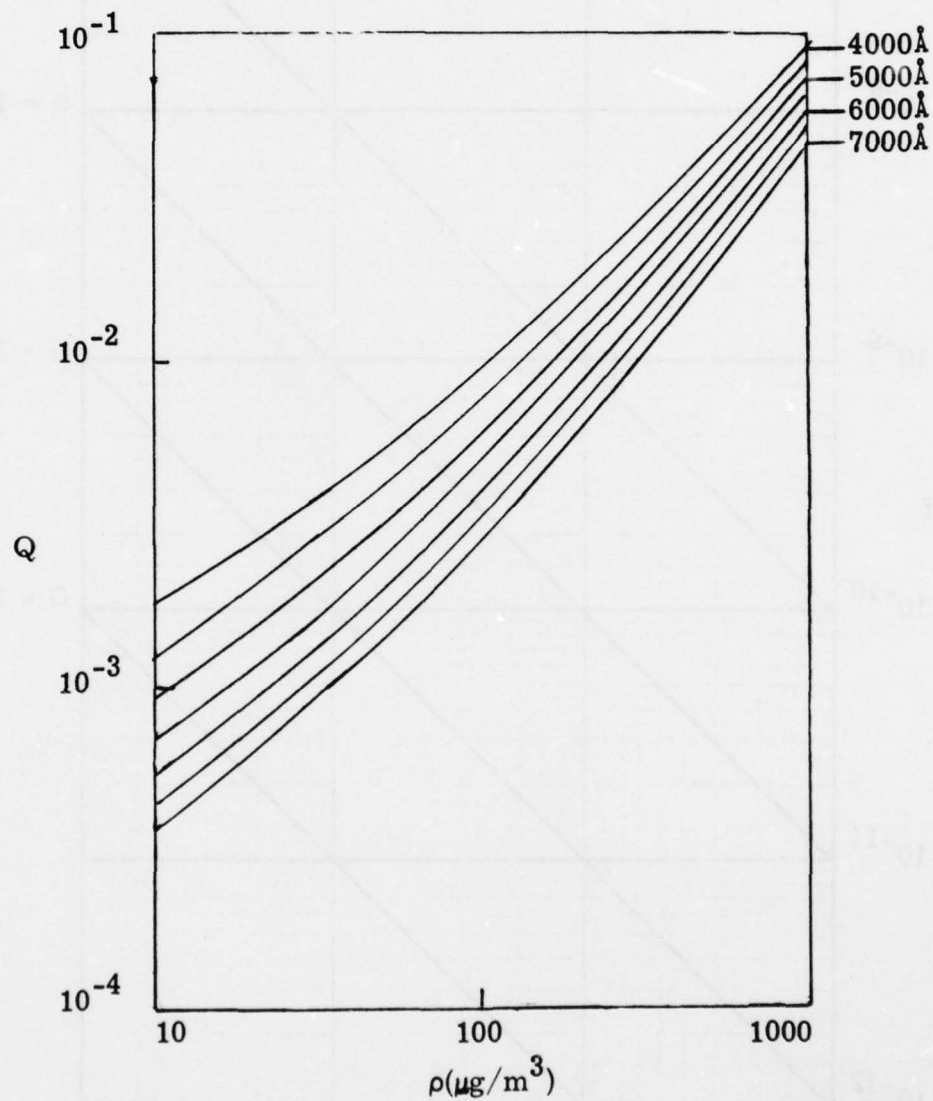


Figure 7.2.5-7 Q versus ρ ($\mu\text{g}/\text{m}^3$) for different wavelengths, assuming a resolution element of 15 m and $\eta_Q = 0.5$

- iii) For a given receiver optics area and overall efficiency, determine G from Figure 7. 2. 5-2.
- iv) Find intersection between G and P_{eff} in Figure 7. 2. 5-4 and determine $\xi(R)$.
- v) Find distance R in Figure 7. 2. 5-3 for a given β_{ext} . The value of β_{ext} may be estimated by dividing 0. 015 into Q , because $Q \approx \beta_{\text{ext}} \Delta R$ and $\Delta R = 0. 015 \text{ km}$.

Example: (i) For a mass density of $300 \mu\text{g}/\text{m}^3$, one finds in Figure 7. 2. 5-5 $Q = 1.8 \times 10^{-2}$ for $\lambda = 5000 \text{ \AA}$. (ii) In Figure 7. 2. 5-6, one finds $P_{\text{eff}} = 9 \times 10^{-8}$. (iii) In Figure 7. 2. 5-4, one finds $G = 240 \text{ Wcm}^2$ for $\eta = .1$ and $A_o = 1000 \text{ cm}^2$. (iv) The intersection in Figure 7. 2. 5-4 between $P_{\text{eff}} = 9 \times 10^{-8} \text{ W}$ and $G = 240 \text{ Wcm}^2$ results in $\xi(R) \approx 5 \times 10^{-10} \text{ cm}^{-2}$. (v) For $\beta_{\text{ext}} = 1.8 \times 10^{-2} / 0. 015 = 1.2$, R becomes about 300 m.

7. 2. 5. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. For particulate matter (TSP), the range of interest is from 60 to $350 \mu\text{g}/\text{m}^3$. This overall range may be divided into three subranges:

Low	60 to $90 \mu\text{g}/\text{m}^3$
Medium	150 to $200 \mu\text{g}/\text{m}^3$
High	250 to $350 \mu\text{g}/\text{m}^3$

The Lidar monitor must measure the TSP density as determined by a reference method for the three ranges to within

Low	$20 \mu\text{g}/\text{m}^3$
Medium	$30 \mu\text{g}/\text{m}^3$
High	$40 \mu\text{g}/\text{m}^3$

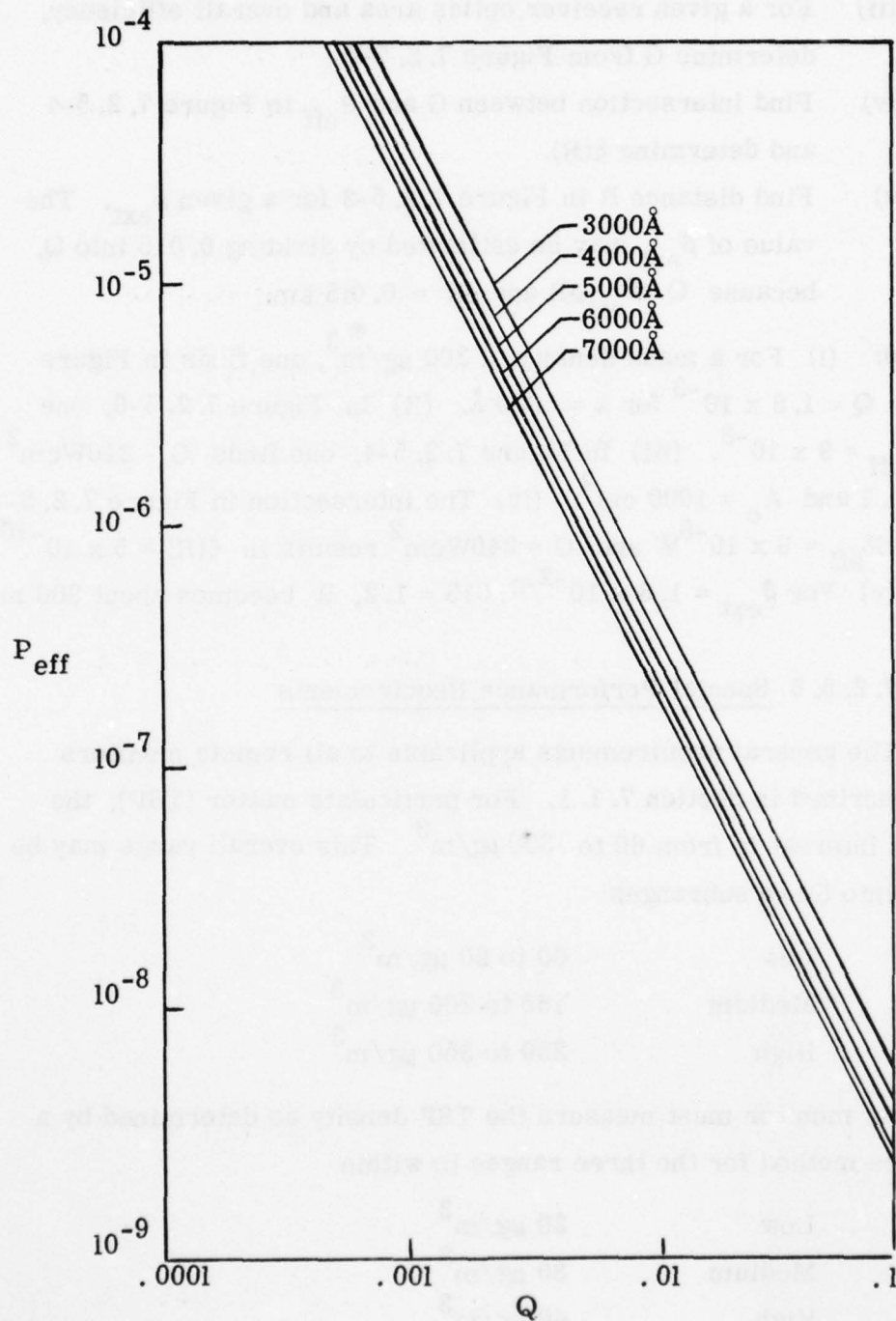


Figure 7.2.5-6 P_{eff} versus Q for $3000 < \lambda < 7000 \text{ Å}$.

However, as was shown in Section 5. 2. 1. 1, the TSP density is not measured directly by an optical method. Thus, either the relationship between extinction and mass density must be firmly established or EPA develops a NAAQS based on the extinction due to TSP.

7. 2. 5. 6 Data Analysis Procedure

The mass density of TSP is determined approximately by

$$\rho(\mu\text{g}/\text{m}^3) = \frac{\beta_{\text{ext}} - \beta_R(\lambda) + 64.0/\lambda(\text{\AA}) - 3.36 \times 10^{-4}}{[12.0/\lambda(\text{\AA})] - 6.3 \times 10^{-5}}$$

where

$$\beta_{\text{ext}} = \frac{\ln Q}{2 \Delta R}$$

$Q = P(R)/P(R+\Delta R)$, as determined according to Figure 7. 2. 5-7, which shows a typical received signal as a function of range.

$\beta_R(\lambda) =$ Rayleigh attenuation coefficient as given in Figure 7. 2. 5-8

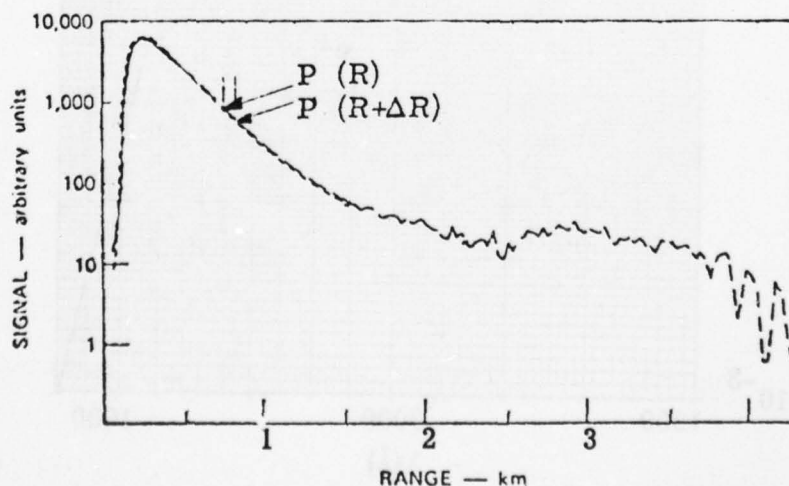
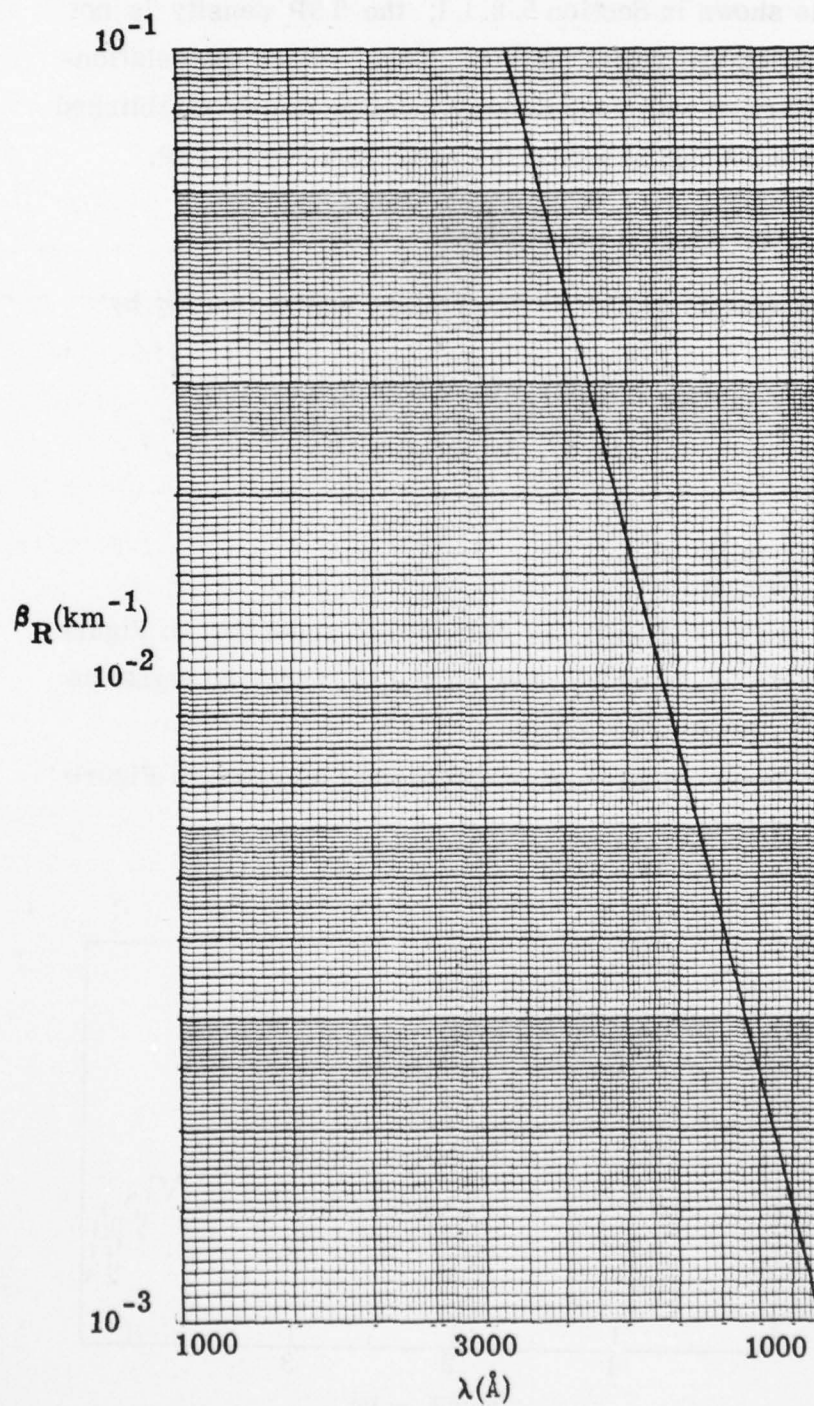


Figure 7. 2. 5-7. Analog Signals $P(R)$, and $P(R+\Delta R)$ vs. Range

Figure 7. 2. 5-8. Rayleigh Attenuation Coefficient vs. λ

7.3 Remote Monitors Providing Line Average Data

7.3.1 LWIR Long-Path with Laser Source

7.3.1.1 Principle of Operation

The measurement principle of long wavelength infrared (LWIR) long-path transmission is used to obtain line averaged concentrations of ozone and certain hydrocarbons. Laser beams at two different wavelengths in the 8-12 μm region are emitted and the transmitted signals are recorded by a receiver. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7.3.1.2 System Description

The system consists of one or two lasers as transmitter, collecting optics, which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) is shown in Figure 7.3.1-1. In order to use a heterodyn detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7.3.1-2).

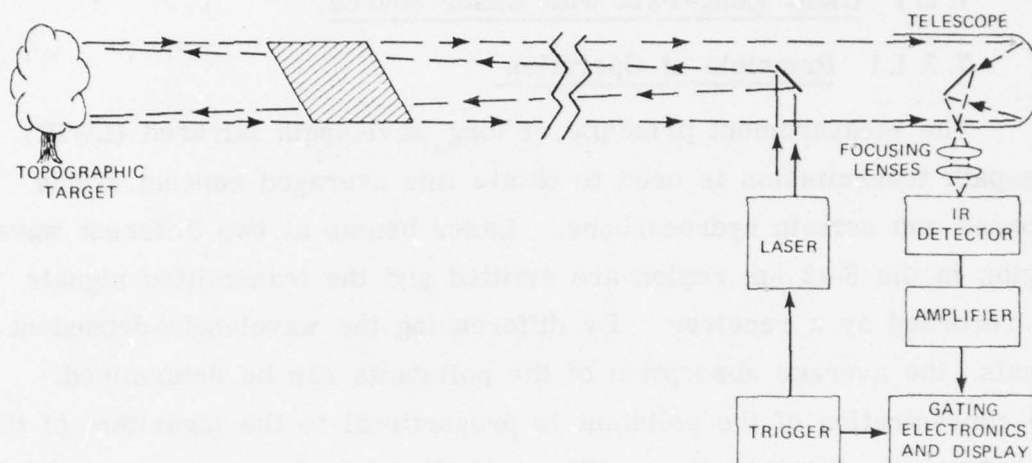


Figure 7. 3. 1-1. Block Diagram for LWIR Long-Path System Using Single Laser and Direct Detection (adopted from Ref. 249).

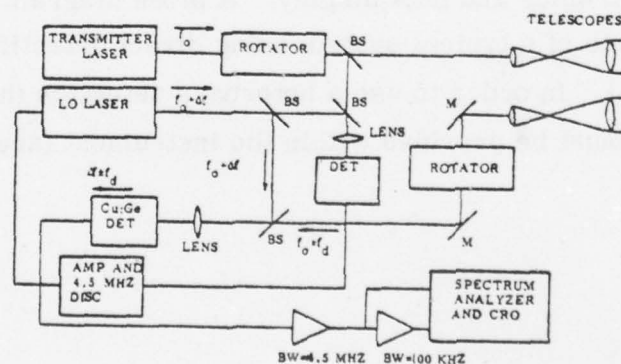


Figure 7. 3. 1-2. Block Diagram for LWIR Long-Path System Using Single Laser and Heterodyne Detection (adopted from Ref. 258).

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DEVELOPMENT OF CRITERIA FOR MONITORING OF AIRPORT GROUND POLLUT--ETC(U)

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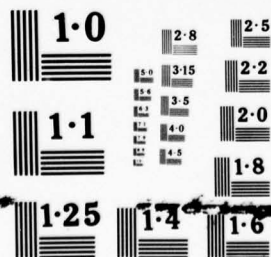
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The hd method is potentially much more sensitive than the dd method and is desirable when a topographical reflector is used. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

7. 3. 1. 3 System Parameters

Commercially Available Lasers

CO₂ Gas Laser
N₂O Gas Laser
Semiconductor-Diode Laser

Other lasers that have transitions in the LWIR region, but are not commercially available at present, include Ne, N₂, Xe, OCS, I, O₂, and HF (Refs. 256 and 257). Both CW and pulsed lasers may be used.

Operational Wavelengths

CO ₂ (00 ⁰ 1-02 ⁰ 0)	P(14)	9.504 μm useful for ozone (Ref. 251)
	P(20)	9.552 μm useful for ozone " "
	P(24)	9.586 μm useful for ozone " "
CO ₂ (00 ⁰ 1-10 ⁰ 0)	P(14)	10.529 μm useful for ethylene (Ref. 251)
	P(16)	10.549 μm useful for ethylene " "
	P(20)	10.588 μm useful for ethylene " "

The coincidence of other transitions of the available lasers to ozone and the hydrocarbons have not been reported as yet.

Laser Energy

For CW lasers, the maximum permissible power is 0.1 W/cm².

Detector

Commercially available detectors with highest D^* and practical risetimes at operating temperatures of 77 K are

Lead-Tin-Telluride ($D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$, $t \sim 10 \text{ ns}$)

Mercury-Cadmium-Telluride ($D^* \sim 3 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$, $t < 1 \text{ ns}$)

These detectors can be made to peak anywhere in the region from 8-12 μm . Active detector areas can range from 0.0025 to 1 mm^2 .

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ($A_o \Omega_o \approx \lambda^2$).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where t_c is the integration time.

7. 3. 1. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned} \ln Q^1 &= \ln \frac{P}{P'} \\ P &= (G/R^2) e^{-2k_1 C R} \\ P' &= (G/R^2) e^{-2k_2 C R} \\ G &= \eta P_t A_o \Gamma(R) \\ \Gamma(R) &\approx 1/(\pi \Omega_o) \quad \text{for retroreflector} \\ \Gamma(R) &= \rho'/\pi \quad \text{for topographical reflector} \\ &\quad \text{(independent of R if reflecting} \\ &\quad \text{surface fills fov)} \\ dP &= \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left(\frac{A_d}{4f_c} \right)^{1/2} (D^*)^{-1}/F \\ F &= \eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} h c D^* \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2} \text{NEP}/F}$$

where

$$Q = 2 \Sigma (k_1 - k_2) C_1 R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

Assume: $D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$

$F \approx 100$ for heterodyne detection

$F = 1$ for direct detection

Result: Plot in Figure 7. 3. 1-3 shows NEP/F (over an adequate range to cover both $F=1$ and $F=100$) versus A_d for different integration times.

Step 2: Calculate: $G = \eta P_t A_o \Gamma(R)$

Assume: $P_t = 1 \text{ W}$ for a laser, having a 10 cm^2 beam area.

Result: Plot in Figure 7. 3. 1-4 shows G versus receiver aperture area A_o for five values of overall efficiency (optical and mechanical shutters) and $\Gamma(R)$.

Step 3: Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 3. 1-5 shows $\xi(R)$ versus R for the above values of kC .

Step 4: Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7. 3. 1-6 which shows P_{eff} vs. $\xi(R)$ for different values of G .

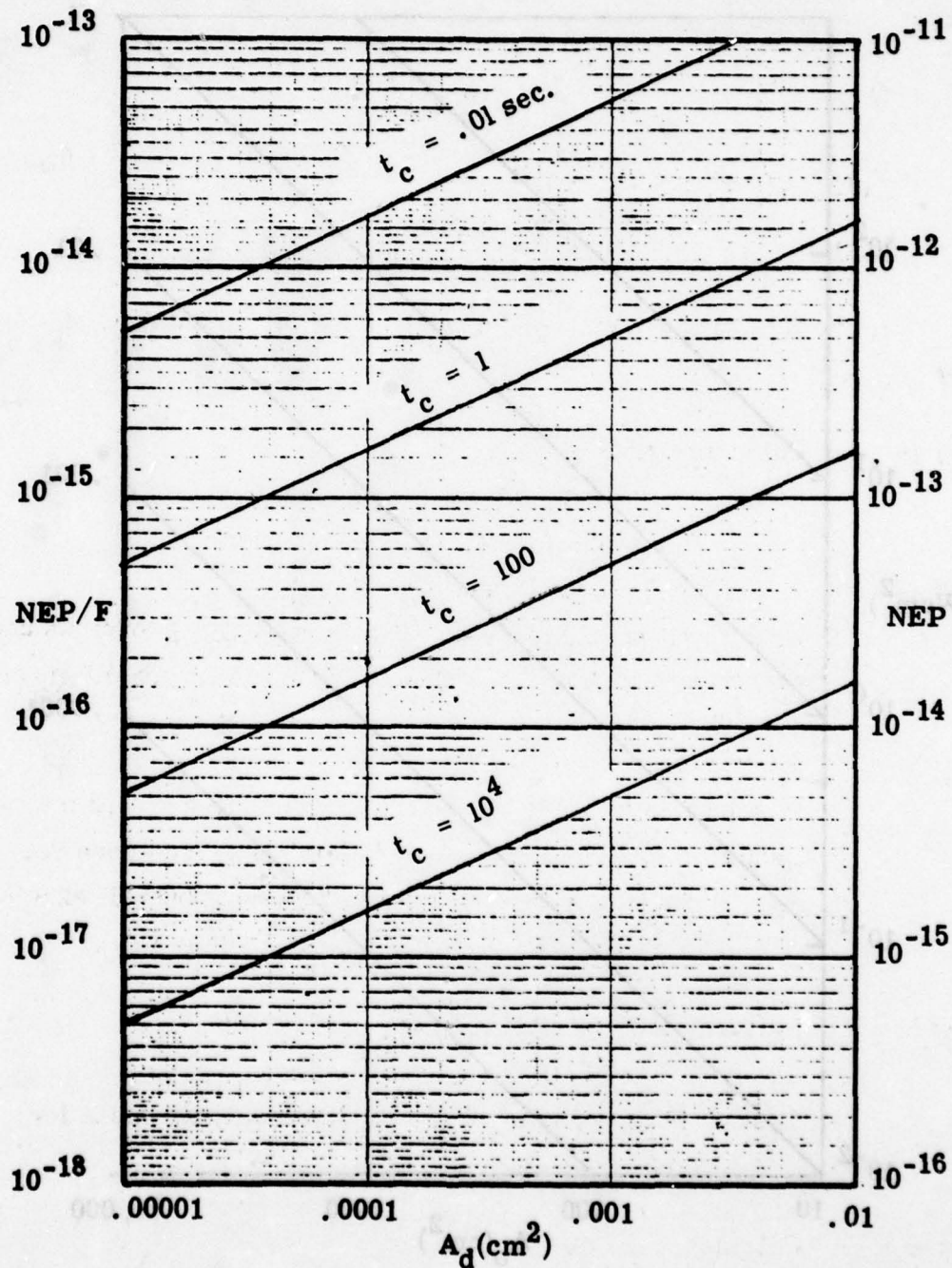


Figure 7. 3. 1-3. NEP versus A_d for Different Values of Integration Times, Assuming $D^* = 3 \times 10^{10}$ cmH^{1/2}W⁻¹.

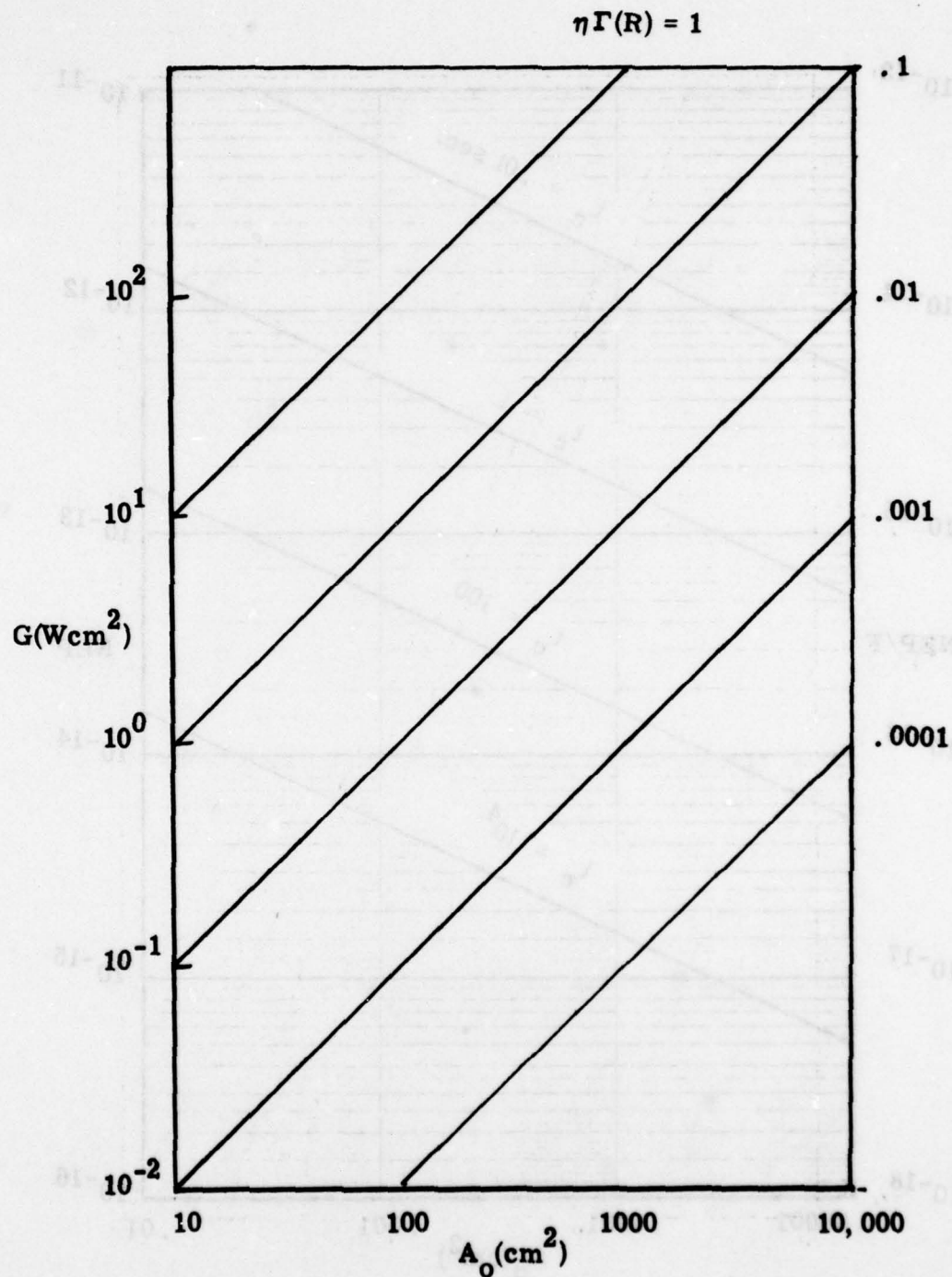


Figure 7. 3. 1-4. Function G versus A_0 for Five Values of $\eta\Gamma$, using $P_t = 1$ W for 10 cm^2 Laser Beam Area.

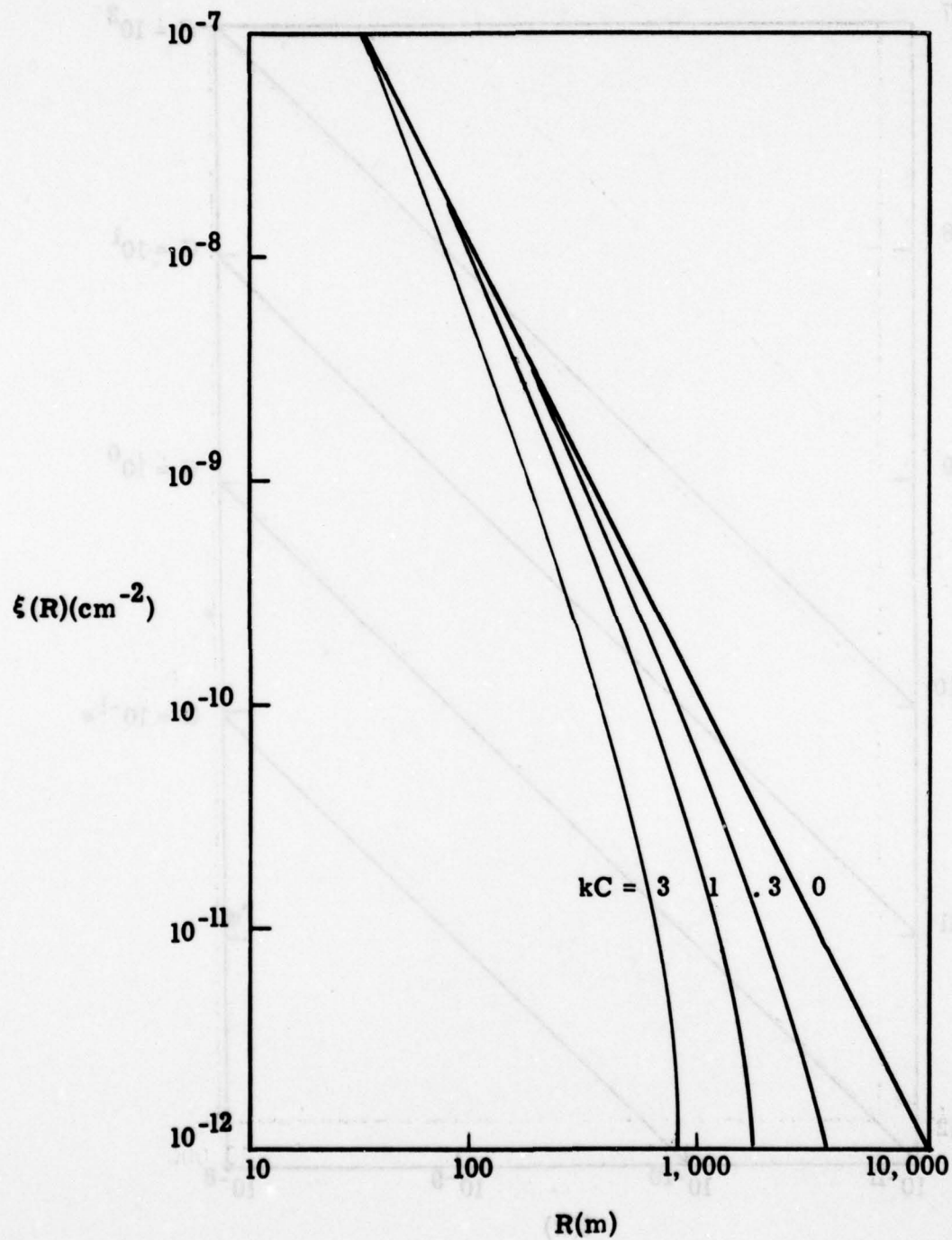


Figure 7. 3. 1-5. Function $\xi(R)$ vs. Range for Different Values of kC (km^{-1})

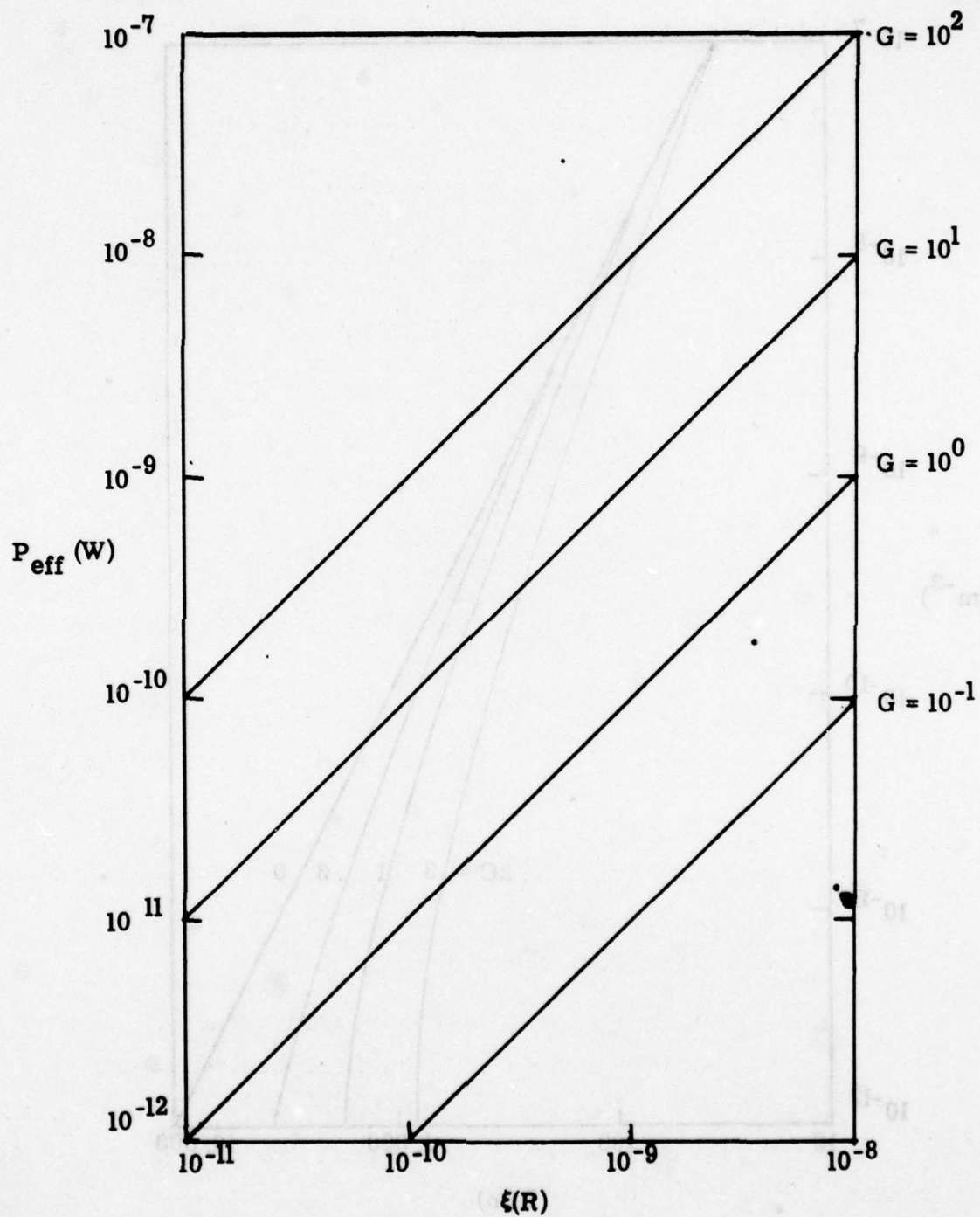


Figure 7. 3. 1-6 P_{eff} versus the Function $\xi(R)$ for Different Values of G

Step 5:

Calculate: Q for ozone (a) and ethylene (b), (including interfering species CO₂ and H₂O)

$$a) \Sigma k_1(9.504\mu\text{m})C_i = k_1(\text{O}_3)C(\text{O}_3) + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) + k_1(\text{CO}_2)C(\text{CO}_2)$$

$$\Sigma k_2(9.586\mu\text{m})C_i = k_2(\text{O}_3)C(\text{O}_3) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) + k_2(\text{CO}_2)C(\text{CO}_2)$$

$$k_1(\text{O}_3) = 1.25 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.11 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_1(\text{CO}_2)C(\text{CO}_2) = 0.123 \text{ km}^{-1} \text{ for 330 ppm}$$

$$k_2(\text{O}_3) = 0.08 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})C_2(\text{H}_2\text{O}) = 0.09 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{CO}_2)C_2(\text{CO}_2) = 0.112 \text{ km}^{-1} \text{ for 330 ppm}$$

$$b) k_1(10.529\mu\text{m})C = k_1(\text{C}_2\text{H}_4)C(\text{C}_2\text{H}_4) + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_2(10.588\mu\text{m})C = k_2(\text{C}_2\text{H}_4)C(\text{C}_2\text{H}_4) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_1(\text{C}_2\text{H}_4) = 2.98 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.12 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{C}_2\text{H}_4) = 0.15 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 0.11 \text{ km}^{-1} \text{ for 10 torr}$$

Result: Plot in Figure 7. 3. 1-7 shows Q for ozone and ethylene versus range for different concentrations.

Step 6:

Calculate: System Performance for SNR = 1, i. e., $\left(P_{\text{eff}}\right)_{\text{min}} = \frac{\sqrt{2} \text{ NEP/F}}{Q}$

i) Determine NEP/F (Step 1)

ii) Calculate Q for desired concentration (Step 5, Figure 7. 3. 1-7)

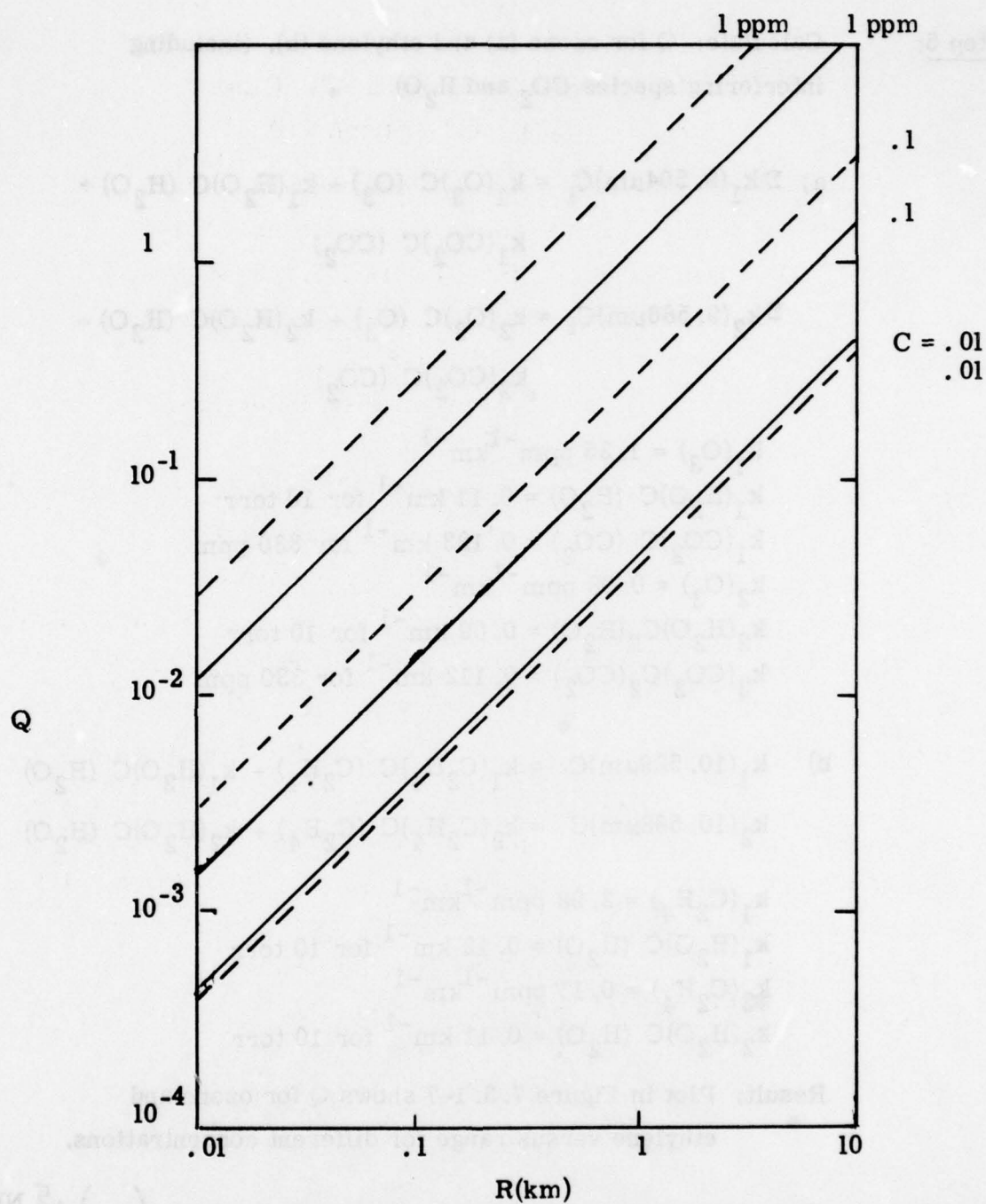
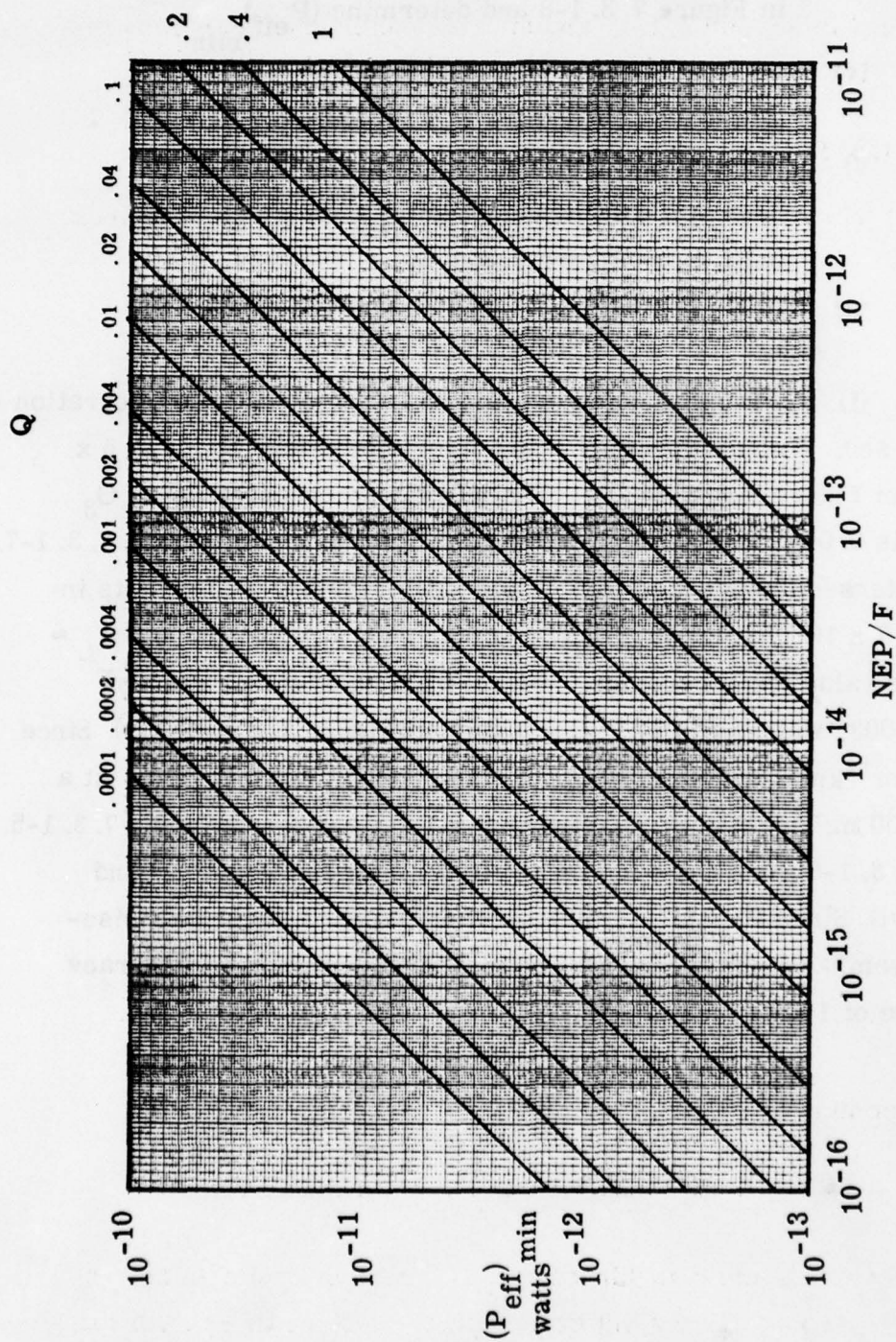


Figure 7. 3. 1-7. Q versus Range for Different Concentrations of Ozone (-) and Ethylene (----).

- iii) Locate intersection between NEP/F and Q in Figure 7. 3. 1-8 and determine $(P_{eff})_{min}$
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7. 3. 1-4.
- v) Determine $\xi(R)$ from Figure 7. 3. 1-5 for given range and kC and establish P_{eff} for given G and ξ from Figure 7. 3. 1-6.
- vi) If $(P_{eff}) > (P_{eff})_{min}$ experiment is feasible.

Example: (i) Assume the detector area is 10^{-3} cm^2 and the integration time is 100 sec. The resulting NEP for direct detection ($F = 1$) is $5 \times 10^{-14} \text{ W}$ from Figure 7. 3. 1-3. (ii) The minimum concentration of O_3 of interest is 0.06 ppm thus $Q = .1$ at a range of 1 km from Figure 7. 3. 1-7. (iii) The intersection between $NEP/F = 5 \times 10^{-14}$ and $Q = .1$ results in $(P_{eff})_{min} = 7 \times 10^{-13} \text{ W}$. (iv) For $A_o = 1000 \text{ cm}^2$, $R = 10^3 \text{ m}$ and $\Omega_L \approx 10^{-6} \text{ sr}$, the value for Γ becomes 0.03. With $\eta = .01$ the product $\eta\Gamma$ becomes .0003, which results in $G = 0.3$ from Figure 7. 3. 1-4. (v) Since $k = 1.25 \text{ ppm}^{-1} \text{ km}^{-1}$ and $C = 0.06 \text{ ppm}$, the product becomes .08. At a range of 1000 m, one finds $\xi(1000 \text{ m}) \approx 9 \times 10^{-11} (\text{cm}^{-2})$ in Figure 7. 3. 1-5. In Figure 7. 3. 1-6, one finds $P_{eff} = 3 \times 10^{-11} \text{ W}$ for $\xi = 9 \times 10^{-11}$ and $G = 0.3$. (vi) Since $(P_{eff})_{min} \approx 40$ indicates that for a detector-noise-limited system, .06 ppm of O_3 may be measured within 2.5% accuracy over a range of 1 km.

Figure 7. 3. 1-8. P_{eff} versus NEP/F for Different Values of Q.

7. 3. 1. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1, and special requirements applicable to ozone and total hydrocarbons were described in Section 7. 2. 1. 5.

7. 3. 1. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{\ln Q}{2 (k_1 - k_2) R}$$

where

$$Q = \frac{P(R)}{P'(R)}$$

The two signals are determined from analog signals. The absorption coefficients k_1 and k_2 are as follows:

	Ozone	Ethylene
$k_1(\text{ppmkm})^{-1}$	1.25 @ 9.504 μm	2.98 @ 10.529 μm
$k_2(\text{ppmkm})^{-1}$	0.08 @ 9.586 μm	0.15 @ 10.588 μm

As previously noted, the coincidence of transitions of available lasers to other hydrocarbons has not yet been reported. Since turbulence can introduce large variations in the received signals, the derivative/ratio signal method has been developed (242, 243).

$$\frac{1}{P_r} \frac{dP_r}{d\omega} = \frac{\delta P_r}{\delta k(\omega)} \frac{\delta k(\omega)}{\delta \omega} \frac{1}{P_r} = \frac{2 k_0 l (\omega - \omega_0) c}{\gamma^2 [1 + (\omega - \omega_0)^2 / \gamma^2]^2}$$

where k_0 is the absorption coefficient at the line center, l is the distance, ω is the laser frequency, ω_0 is the frequency at the line center, c is the pollutant concentration, and γ is the half-width at half-height. For a given laser frequency the signal is directly proportional to the pollutant concentration. For maximum sensitivity, the ratioed signal should be evaluated at a laser frequency where the slope of the absorption line is greatest. The only exception is when the pollutant concentration is so high that most of the laser power is absorbed. In such instances a weaker line should be selected.

The signal $[(dPr/d\omega)/Pr]$ as a function of pollutant concentration can be obtained from laboratory and/or field calibration. The calibration is made by using a gas cell with a known amount of pollutant gas. This can be done during the actual field test by observing the signal change after inserting the gas cell. An example of such a calibration was shown in Figure 2.5-39.

7.3.2 MWIR Long-Path with Laser Source

7.3.2.1 Principle of Operation

The measurement principle of medium wavelength infrared (MWIR) long-path transmission is used to obtain line-averaged concentrations of carbon monoxide and nitrous oxide. Laser beams at two different wavelengths in the 4.8-5.4 μm region are emitted and the transmitted signals are recorded by a receiver. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7.3.2.2 System Description

The system consists of one or two lasers as transmitter, collecting optics which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) is basically the same as was shown for the LWIR system in Figure 7.3.1-1. In order to use a heterodyn detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7.2.1-2). The hd method is potentially somewhat more sensitive than the dd method. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

7. 3. 2. 3 System Parameters

Commercially Available Lasers

Dbl CO₂ Pumped Spinflip Gas Laser

CO Gas Laser

Semiconductor-Diode Laser

Other lasers that have transitions in the MWIR region, but are not commercially available at present, include DCl, Ar, CN, Kr, H₂O, Xe, I, and O₂ (Refs. 256 and 257). Both CW and pulsed lasers may be used.

Operational Wavelengths

CO, 6-5, P(20)	5.176 μm	useful for NO	(Ref. 251)
7-6, P(13)	5.166 μm	useful for NO	" "
7-6, P(15)	5.187 μm	useful for NO	" "
9-8, P(9)	5.262 μm	useful for NO	" "
Diode Laser	4.755 μm	useful for CO	(Ref. 242)
	4.746 μm	useful for CO	" "
	4.702 μm	useful for CO	" "

The coincidence of other transitions of the available lasers to carbon monoxide and nitrous oxide have not been reported as yet. The CO gas laser cannot be used to observe CO in the atmosphere since the lowest observed vibrational transition in the laser is in the 5-4 band [P(18) and up], which is too high an energy level to be populated at atmospheric temperatures.

Laser Energy

For CW lasers, the maximum permissible power is 0.1 W/cm².

Detector

Commercially available detectors with highest D^* and practical risetimes at operating temperatures of 77K are

Indium-Antimonide ($D^* \sim 10^{11} \text{ cm Hz}^{1/2}/\text{W}$, $t < 1\mu\text{s}$)

Gold-doped Germanium ($D^* \sim 2 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$, $t \sim 1\mu\text{s}$)

Active detector areas can range from 0.008 to 1 mm^2 .

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (=A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ($A_o \Omega_o \approx \lambda^2$).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where t_c is the integration time.

7. 3. 2. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned} \ln Q^1 &= \ln \frac{P}{P'} \\ P &= (G/R^2)e^{-2k_1 C R} \\ P' &= (G/R^2)e^{-2k_2 C R} \\ G &= \eta P_t A_o \Gamma(R) \\ \Gamma(R) &\approx 1/(\pi \Omega_L) \text{ for retroreflector} \\ \Gamma(R) &= \rho'/\pi \text{ for topographical reflector} \\ &\quad \text{(independent of R if reflecting surface fills fov)} \\ dP &= \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left(\frac{A_d}{4t_c} \right)^{1/2} (D^*)^{-1}/F \\ F &= \eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} h c D^* \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2} \text{NEP}/F}$$

where

$$Q = 2\Sigma(k_1 - k_2)i C_i R$$

$$P_{\text{eff}} = G\xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

Assume: $D^* = 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$

$F = 10$ for heterodyne detection

$F = 1$ for direct detection

Result: Plot in Figure 7.2.2-1 shows NEP/F (over an adequate range to cover both $F=1$ and $F=100$) versus A_d for different integration times

Step 2: Calculate: $G = \eta P_t A_o \Gamma(R)$

Assume: $P_t = 1 \text{ W}$ for a laser having a 10 cm^2 beam area

Result: Plot in Figure 7.3.2-2 shows G versus receiver aperture area A_o for five values of overall efficiency (optical and mechanical shutters) and $\Gamma(R)$

Step 3: Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.3.2-3 shows $\xi(R)$ versus R for the above values of kC

Step 4: Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7.3.2-4 which shows P_{eff} vs. $\xi(R)$ for different values of G .

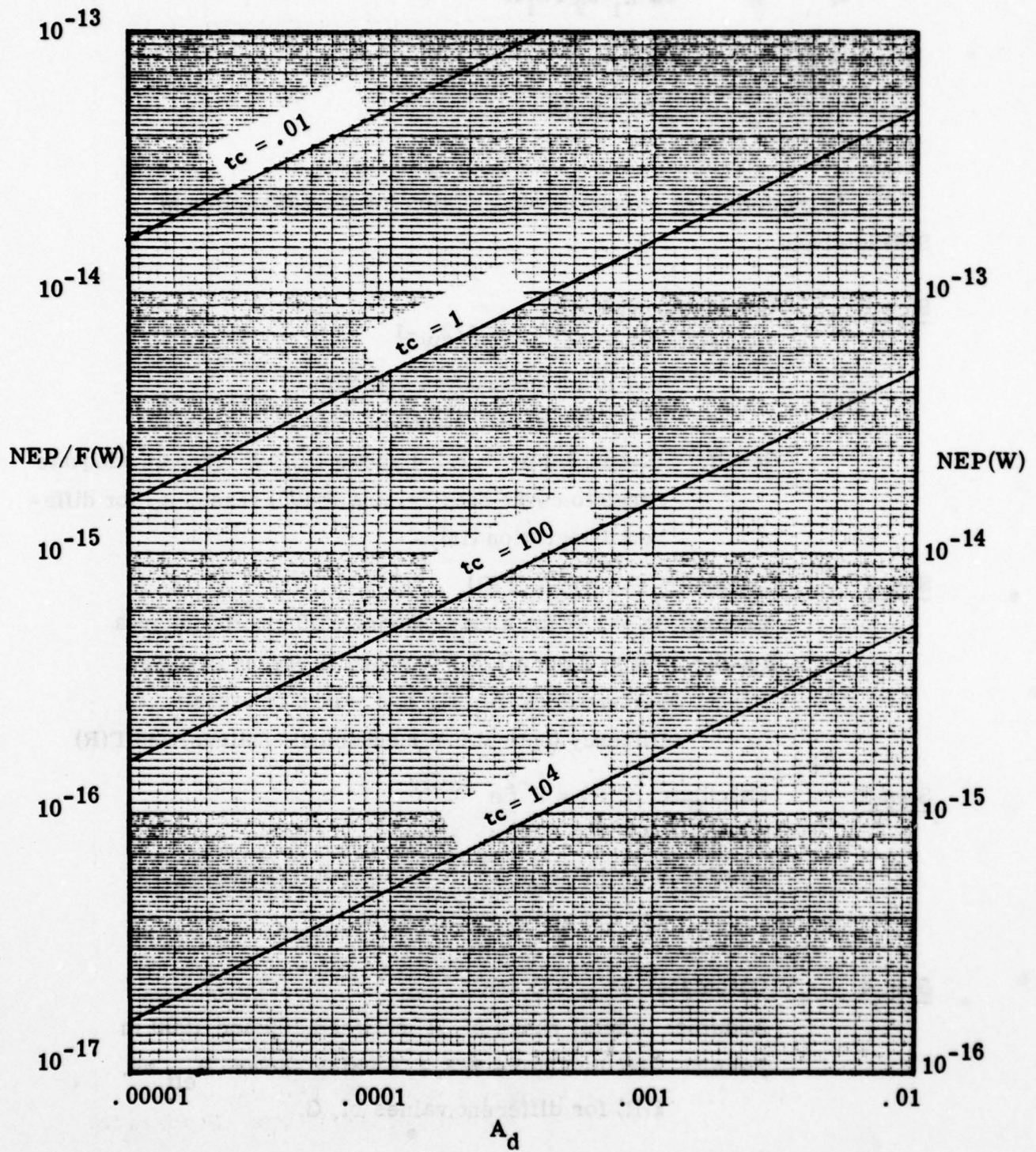


Figure 7. 3. 2-1. NEP versus A_d for Different Values of Integration Time, Assuming $D^* = 10^{11} \text{ cmH}^{1/2} \text{ W}^{-1}$.

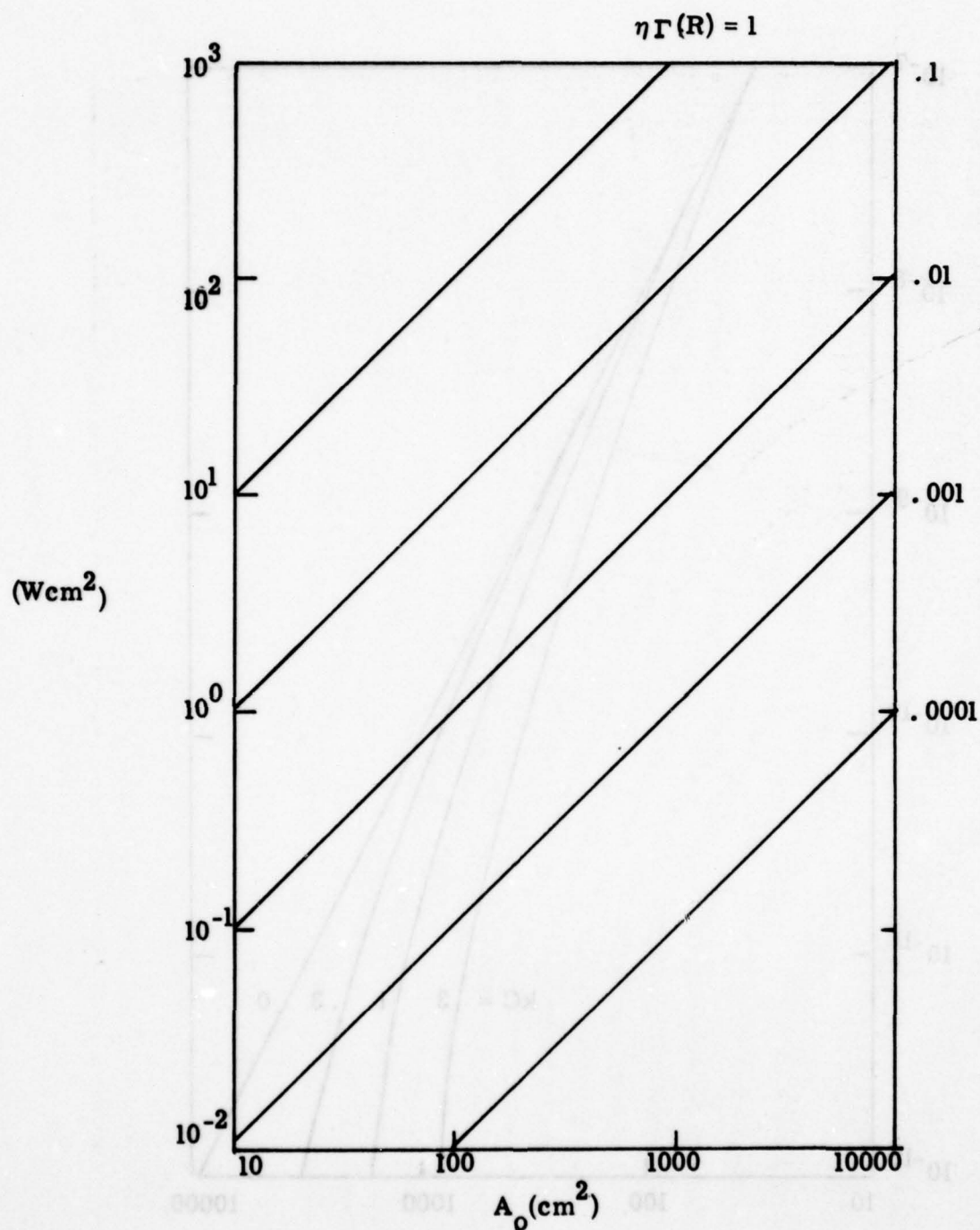


Figure 7. 3. 2-2. Function G versus A_0 for Five Values of $\eta \Gamma$ using $P_t = 1 \text{ W}$ for 10 cm^2 Laser Beam Area.

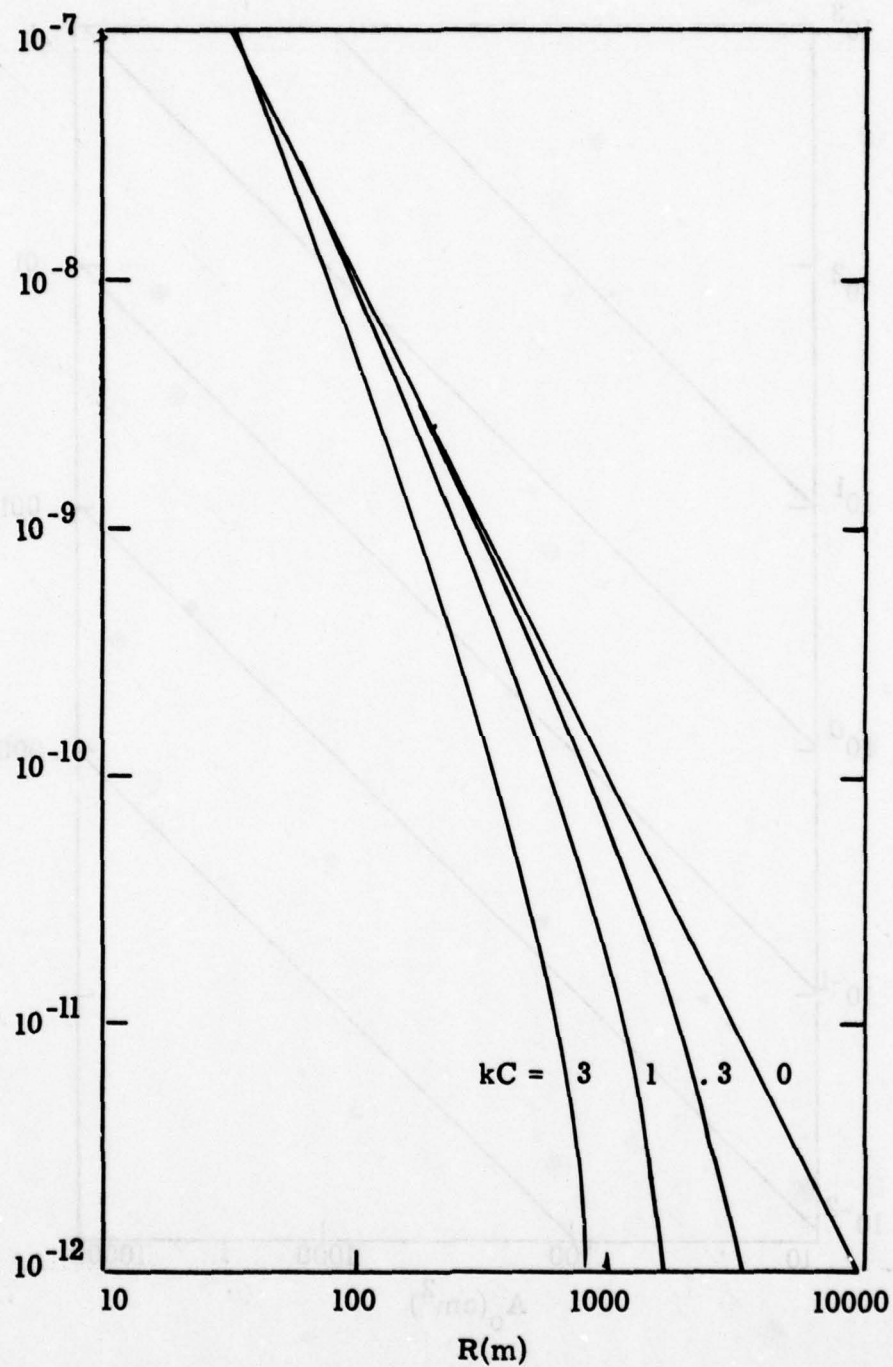


Figure 7. 3. 2-3. Function $\xi(R)$ vs. Range for Different Values of kC (km^{-1}).

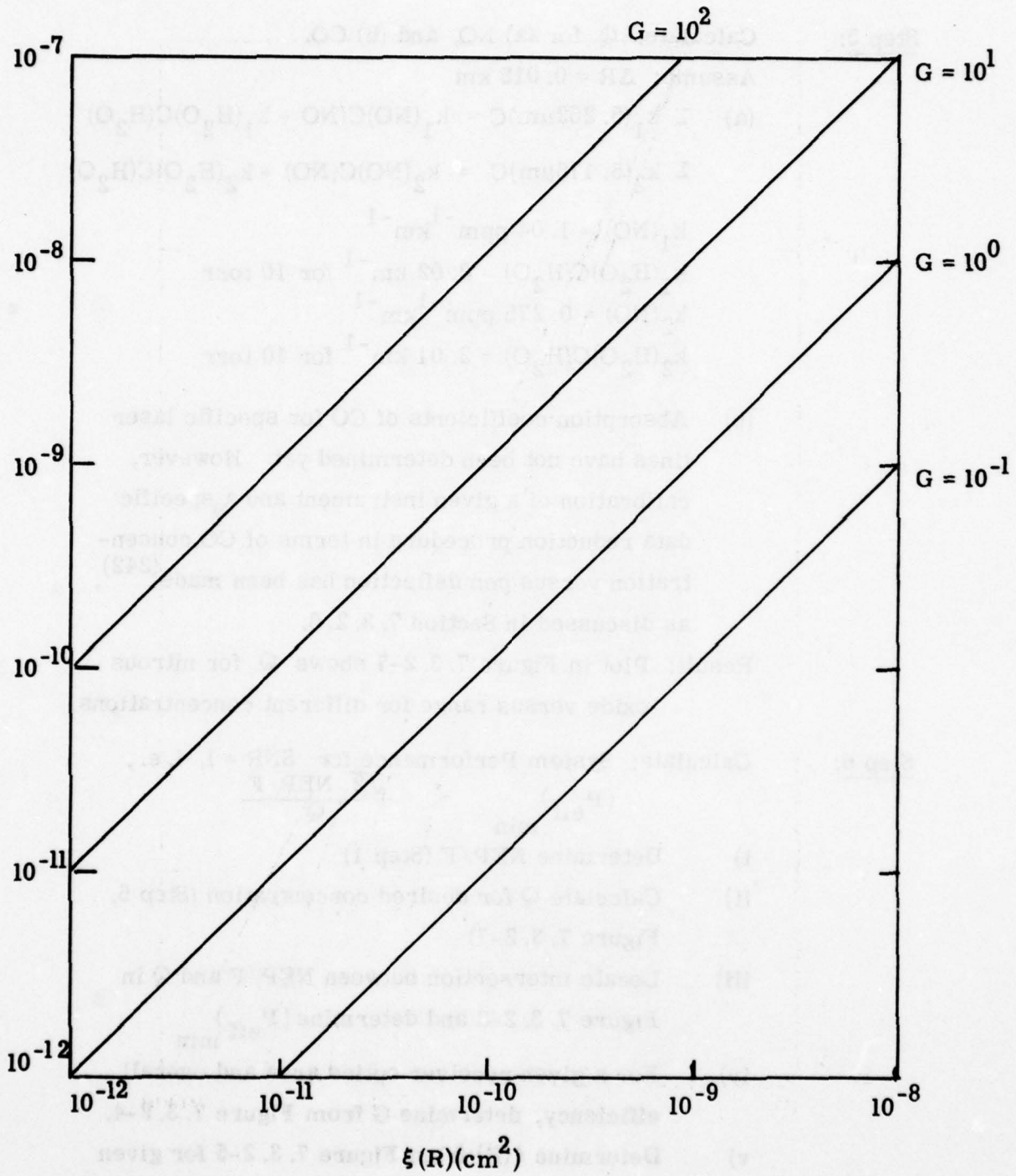


Figure 7. 3. 2-4. P_{eff} versus the Function $\xi(R)$ for Different Values of G .

Step 5: Calculate: Q for (a) NO, and (b) CO.

Assume: $\Delta R = 0.015 \text{ km}$

$$\begin{aligned} \text{(a)} \quad \Sigma k_1(5.262\mu\text{m})C &= k_1(\text{NO})C(\text{NO} + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O})) \\ \Sigma k_2(5.176\mu\text{m})C &= k_2(\text{NO})C(\text{NO}) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) \\ k_1(\text{NO}) &= 1.04 \text{ ppm}^{-1}\text{km}^{-1} \\ k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) &= 2.02 \text{ km}^{-1} \text{ for 10 torr} \\ k_2(\text{NO}) &= 0.275 \text{ ppm}^{-1}\text{km}^{-1} \\ k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) &= 2.01 \text{ km}^{-1} \text{ for 10 torr} \end{aligned}$$

- (b) Absorption coefficients of CO for specific laser lines have not been determined yet. However, calibration of a given instrument and a specific data reduction procedure in terms of CO concentration versus pen deflection has been made⁽²⁴²⁾, as discussed in Section 7. 3. 2. 6.

Result: Plot in Figure 7. 3. 2-7 shows Q for nitrous oxide versus range for different concentrations.

Step 6: Calculate: System Performance for $\text{SNR} = 1$, i. e.,

$$(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{ NEP/F}}{Q}$$

- i) Determine NEP/F (Step i)
- ii) Calculate Q for desired concentration (Step 5, Figure 7. 3. 2-7)
- iii) Locate intersection between NEP/F and Q in Figure 7. 3. 2-8 and determine $(P_{\text{eff}})_{\text{min}}$
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7. 3. 2-4.
- v) Determine $\xi(R)$ from Figure 7. 3. 2-5 for given range and kC and establish P_{eff} for given G and ξ from Figure 7. 3. 2-6.
- vi) If $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$ experiment is feasible.

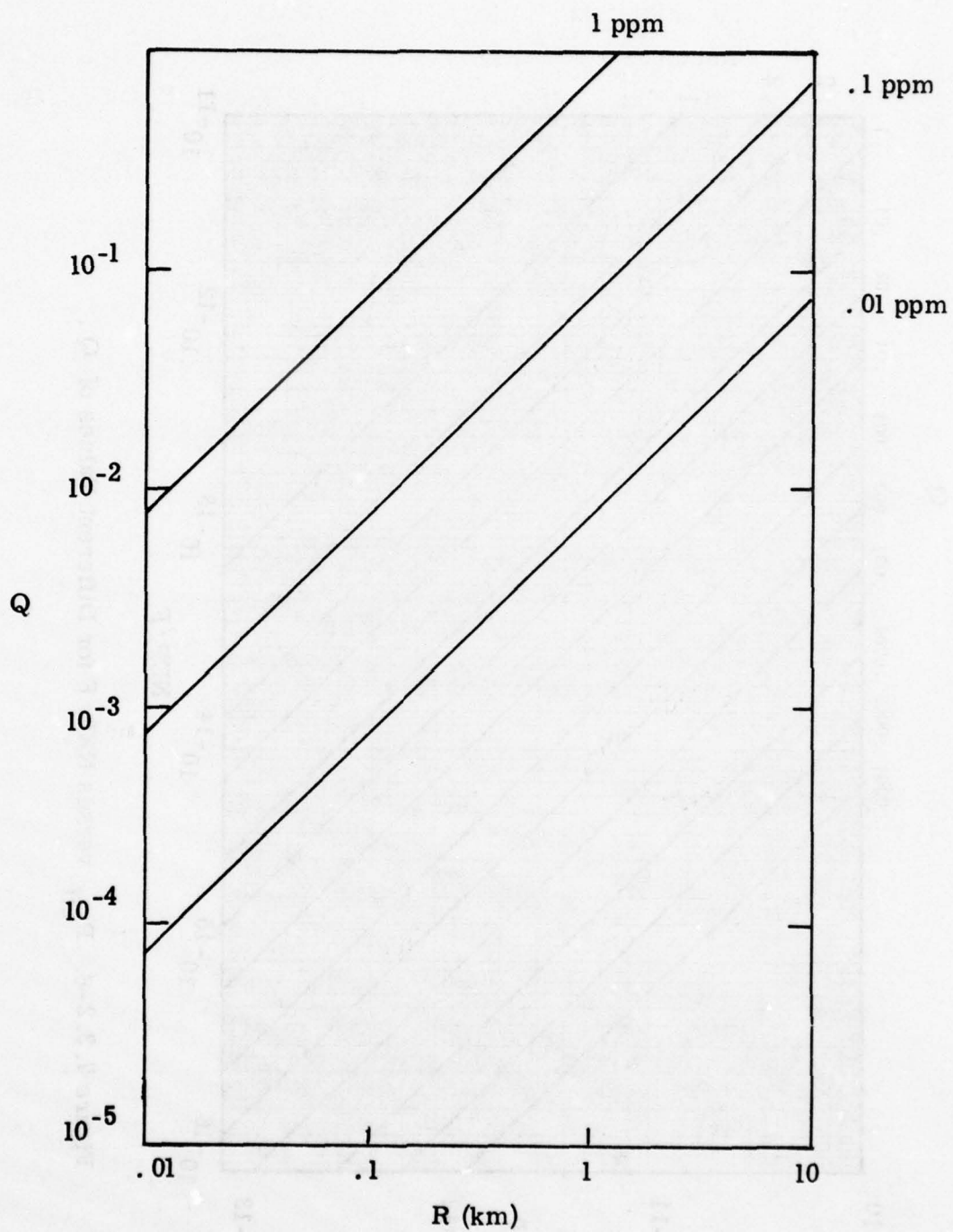


Figure 7. 3. 2-5. Q versus Range for Different Concentrations of NO

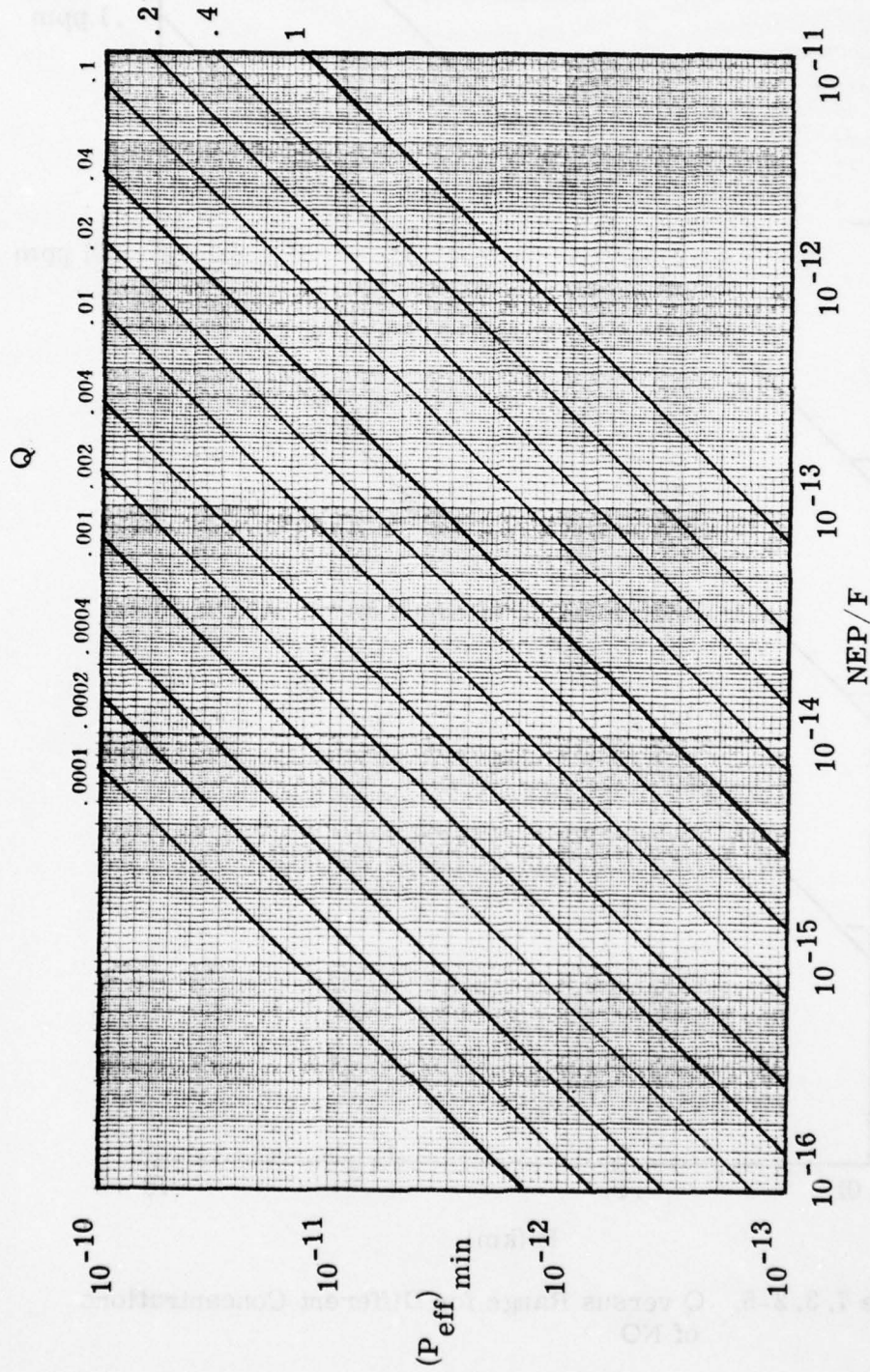


Figure 7. 3. 2-6. P_{eff} versus NEP/F for Different Values of Q .

7. 3. 2. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. For NO_x and CO, the special requirements were described in Section 7. 2. 2. 5.

7. 3. 2. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{\ln Q}{2(k_1 - k_2)}$$

where

$$Q = \frac{P(R)}{P'(R)}$$

The two signals are determined from analog signals. The absorption coefficients k_1 and k_2 are as follows:

	NO
$k_1(\text{ppmkm})^{-1}$	1.04 @ 5.262 μm
$k_2(\text{ppmkm})^{-1}$	0.275 @ 5.176 μm

Since turbulence can introduce large variations in the received signals, the derivative/ratio signal method has been developed^(242, 243)

Mathematically, this method is expressed as

$$\frac{1}{P_r} \frac{d P_r}{d \omega} = \frac{\delta P_r}{\delta k(\omega)} \frac{\delta k(\omega)}{\delta \omega} \frac{1}{P_r} = \frac{2 k_0 \ell (\omega - \omega_0) c}{\gamma^2 [1 + (\omega - \omega_0)^2 / \gamma^2]^2}$$

where k_0 is the absorption coefficient at the line center, ℓ is the distance, ω is the laser frequency, ω_0 is the frequency at the line center, c is the pollutant concentration, and γ is the half-width at half-height. For a given laser frequency the signal is directly proportional to the pollutant concentration. For maximum sensitivity, the ratioed signal should be evaluated at a laser frequency where the slope of the absorption line is greatest. The only exception is when the pollutant concentration is so high that most of the laser power is absorbed. In such instances a weaker line should be selected.

The signal $[(d P_r/d \omega)/P_r]$ as a function of CO concentration is obtained from laboratory and/or field calibration for a given instrument in terms of pen deflection⁽²⁴²⁾. The calibration is made by using a gas cell with a known amount of pollutant gas. This was done during the actual field test by observing the signal change after inserting the gas cell.

7.3.3 SWIR Long-Path with Laser Source

7.3.3.1 Principle of Operations

The measurement principle of short wavelength infrared (SWIR) long-path transmission is used to obtain line-averaged concentrations in the 2.5-4 μm region (NO_x , SO_2) and hydrocarbons. Laser beams at two different wavelengths are emitted and the transmitted signals are recorded. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7.3.3.2 System Description

The system consists of one or two lasers as transmitter, collecting optics which can be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct direction (dd) is basically the same as was shown for the LWIR system in Figure 7.3.3-1. Heterodyne detection (hd) is not useful for SWIR. It should be noted that no prototype SWIR-Long-path system, using two lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

7.3.3.3 System Parameters

Commercially Available Lasers

HF Gas Laser
DF Gas Laser

Other lasers that have transitions in the SWIR region, but are not commercially available at present, include Kr, Ne, Ar, I, Xe, Br, O₂, Cl, Cs, N₂, C, HCl and HBr (Refs. 256 and 257). Both CW and pulsed lasers may be used.

Operational Wavelengths

Have not been determined yet.

Laser Energy

For CW lasers, the maximum permissible power is 0.1 W/cm².

Detector

Commercially available detectors with highest D* and practical risetimes at operating temperatures of 200 K are

Lead-Sulfide *D*~3 x 10¹¹ cm Hz^{1/2}/W, t~300 μsec)

Active areas can range from 0.0001 to several mm².

Optics

Collecting Aperture	A _o
Solid Angle	Ω _o
Optical Efficiency	η _{opt}
Detector Optics	A _d Ω _d (=A _o Ω _o)

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where t_c is the integration time, which may be increased to optimize the SNR.

7. 3. 3. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned} \ln Q^1 &= \ln \frac{P}{P'} \\ P &= (G/R^2)e^{-2k_1 C R} \\ P' &= (G/R^2)e^{-2k_2 C R} \\ G &= \eta P_t A_o \Gamma(R) \\ \Gamma(R) &\approx 1/(\pi \Omega_o) \text{ for retroreflector} \\ \Gamma(R) &= \rho'/\pi \text{ for topographical reflector} \\ &\quad \text{(independent of R if reflecting surface fills fov)} \\ dP &= \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left(\frac{A_d}{4t_c} \right)^{1/2} (D^*)^{-1}/F \\ F &= \eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} h c D^* \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2} \text{NEP}/F}$$

where

$$Q = 2 \sum (k_1 - k_2)_i C_i R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

$$\text{Assume: } D^* = 3 \times 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

$$F = 1$$

Result: Plot in Figure 7. 3. 3-1 shows NEP versus A_d for different integration times.

Step 2: Calculate: $G = \eta P_t A_o \Gamma(R)$

Assume: $P_t = 1 \text{ W}$ for a laser having a 10 cm^2 beam area.

Result: Plot in Figure 7. 3. 3-2 shows G versus receiver aperture area A_o for five values of overall efficiency (optical and mechanical shutters) and $\Gamma(R)$.

Step 3: Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 3. 3-3 shows $\xi(R)$ versus R for the above values of kC

Step 4: Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7. 3. 3-4 which shows P_{eff} vs. $\xi(R)$ for different values of G.

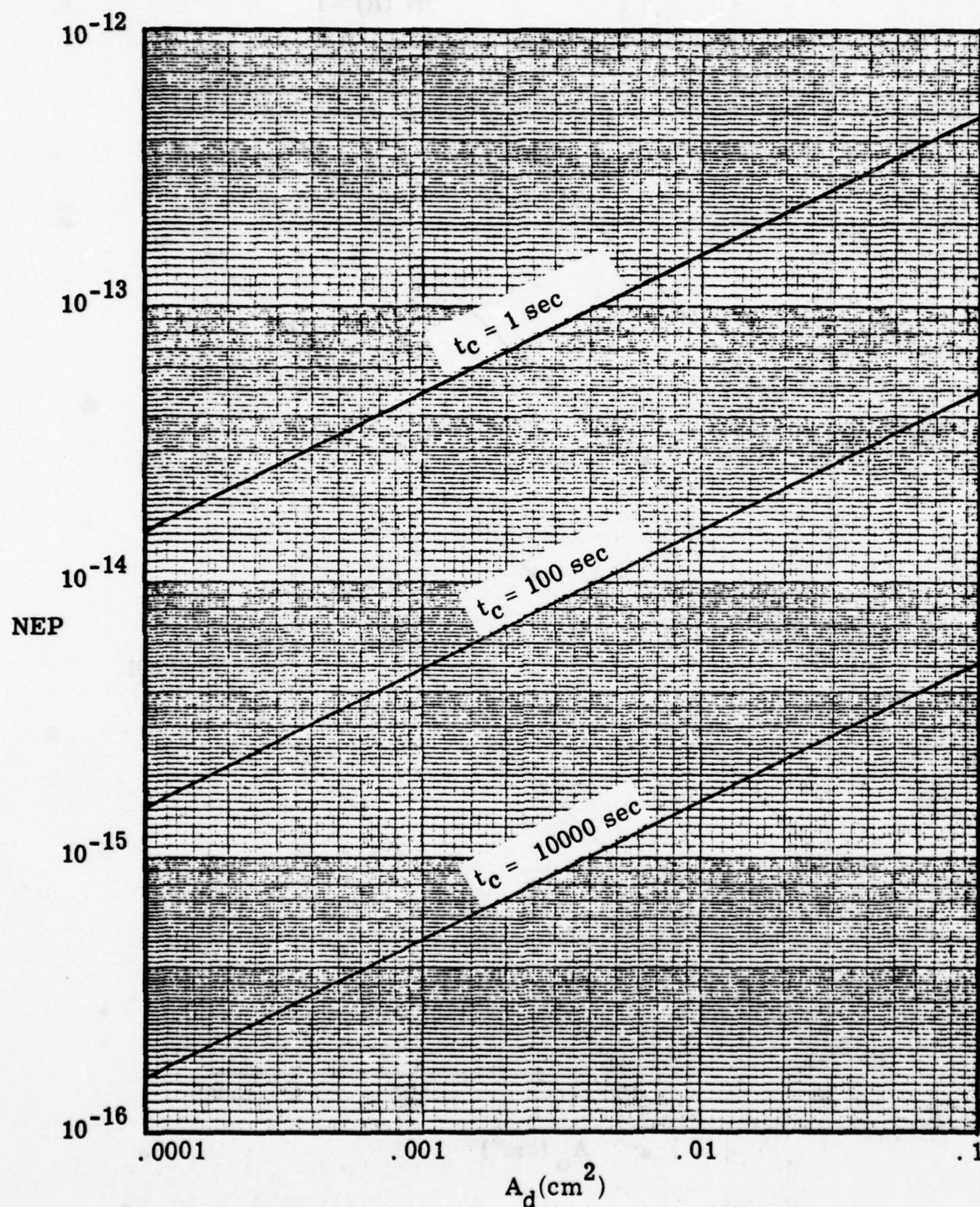


Figure 7. 3. 3-1. NEP versus A_d for Different Values of Integration Times Assuming $D^* = 3 \times 10^{11} \text{ cm H}^{1/2} \text{ W}^{-1}$.

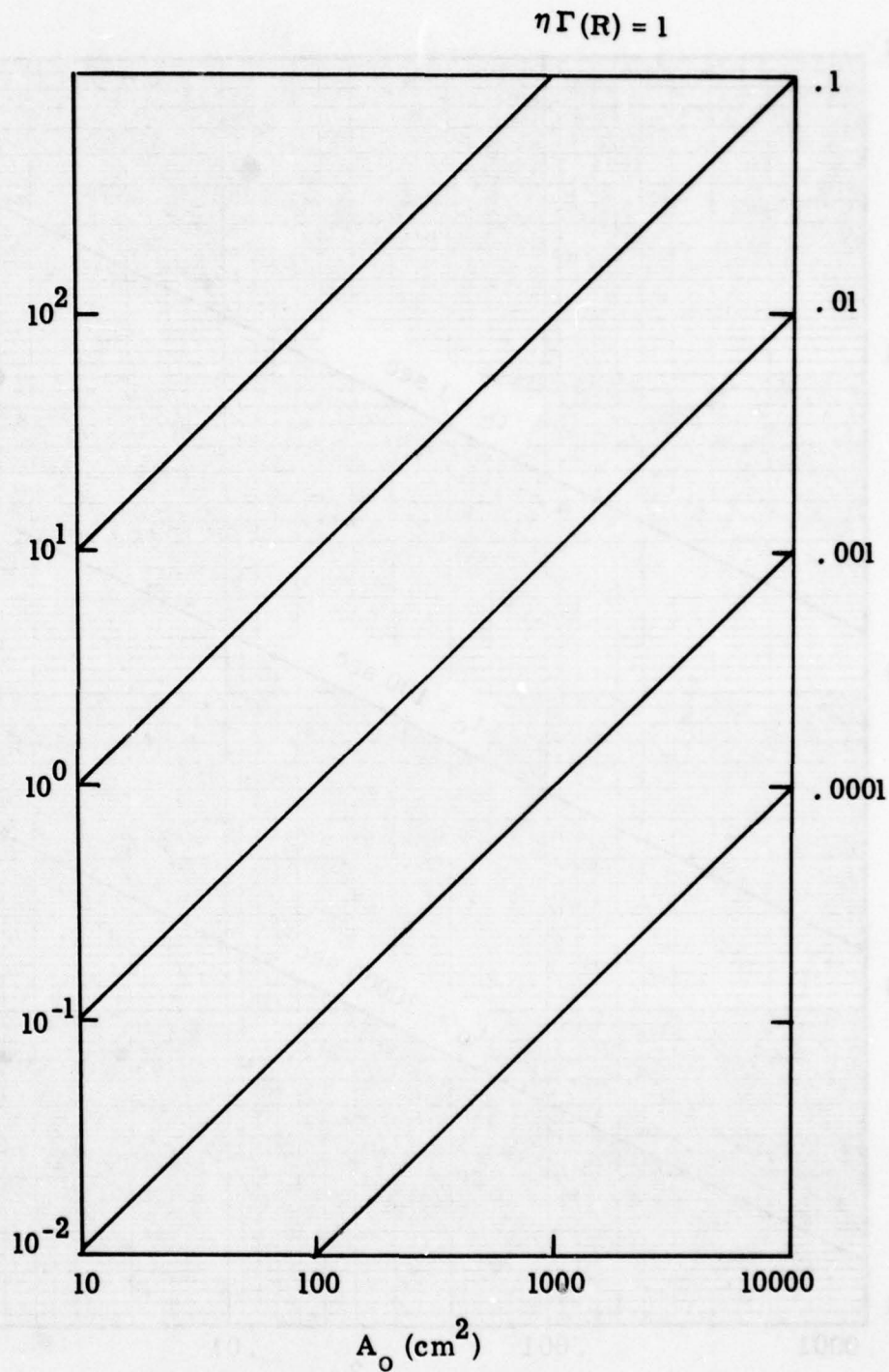


Figure 7.3.3-2. Function G versus A_0 for Five Values of $\eta \Gamma$,
Using $P_r = 1$ for 10 cm² Laser Beam Area.

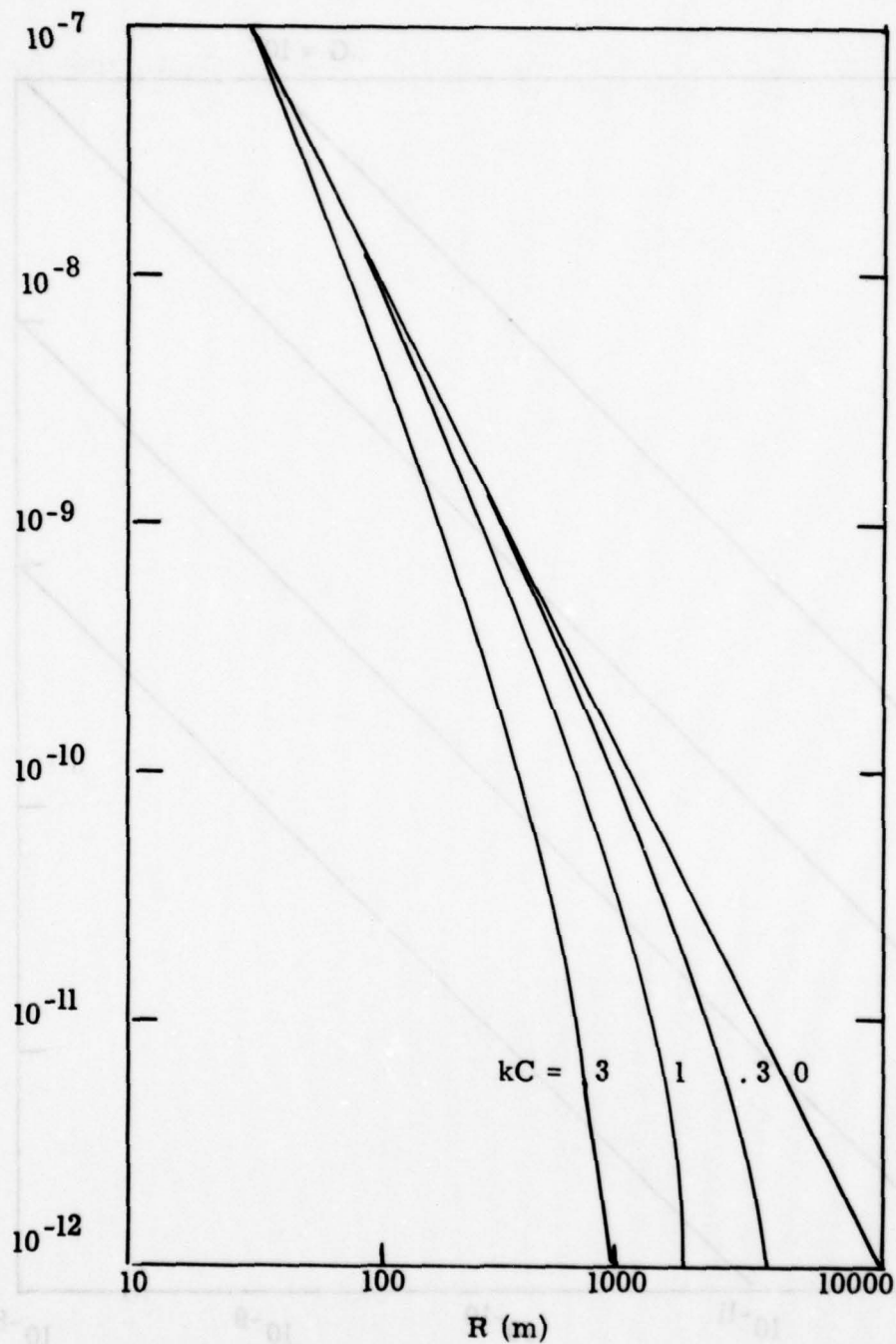


Figure 7.3.3.-3. Function $\xi(R)$ versus Range for Different Values of kC (km^{-1})

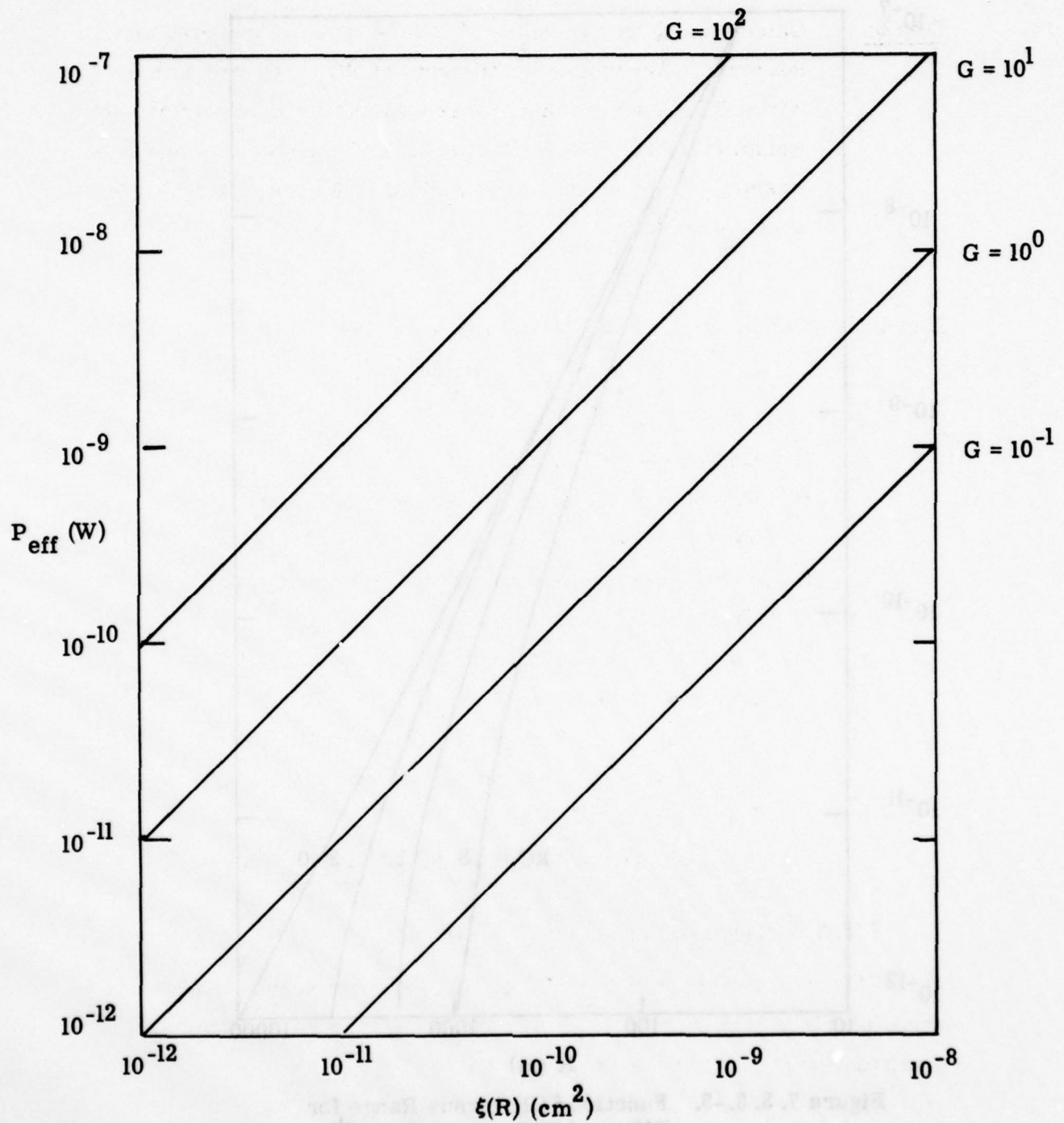


Figure 7. 3. 3-4. P_{eff} versus the Function $\xi(R)$ for Different Values of G

Step 5: Calculate: Q for (a) NO_x , and (b) SO_2 and (c) hydrocarbons
Assume: Absorption coefficients of NO_x , SO_2 and hydrocarbons for specific laser lines have not been determined yet. Actual calculation cannot be performed until data is available.
Result: Q versus C to be plotted in Figure 7.3.3.-5 when data is available.

Step 6: Calculate: System Performance for $\text{SNR} = 1$, i. e.,

$$(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{NEP}/F}{Q}$$

- i) Determine NEP/F (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7.3.3.-5)
- iii) Locate intersection between NEP/F and Q in Figure 7.3.3-6 and determine $(P_{\text{eff}})_{\text{min}}$.
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7.3.3-4.
- v) Determine $\xi(R)$ from Figure 7.3.3-3 for given range and kC and establish P_{eff} for given G and ξ from Figure 7.3.3-4.
- vi) If $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$, experiment is feasible.

7.3.3.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For SO_2 , THC and NO_x the special requirements were listed in Section 7.2.3.5.

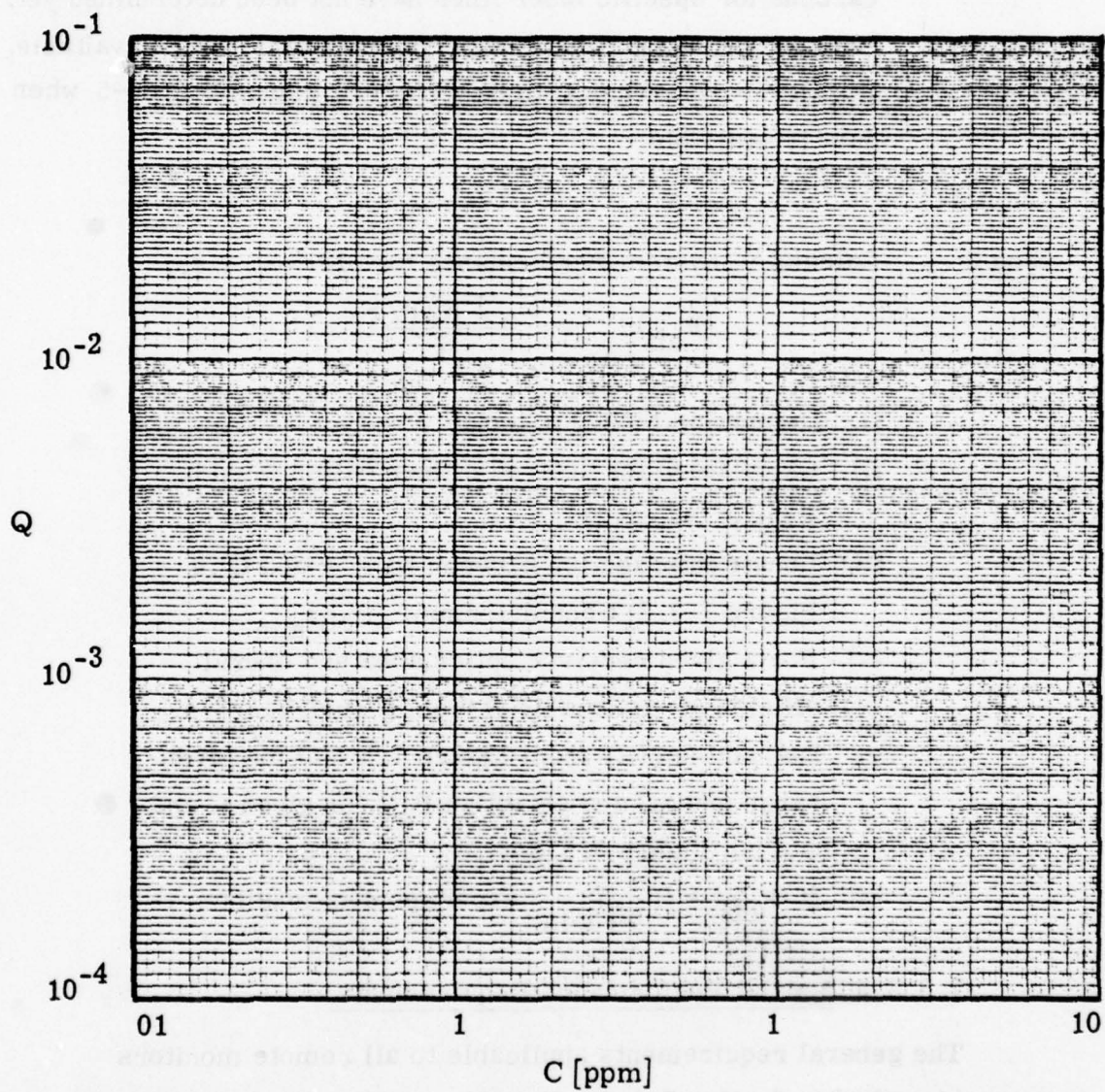


Figure 7. 3. 3-5. Q versus Concentration of NO_x , SO_2 and $\langle \text{HC} \rangle$ for Different Ranges

See Step 5, Data required for this graph is not yet determined.

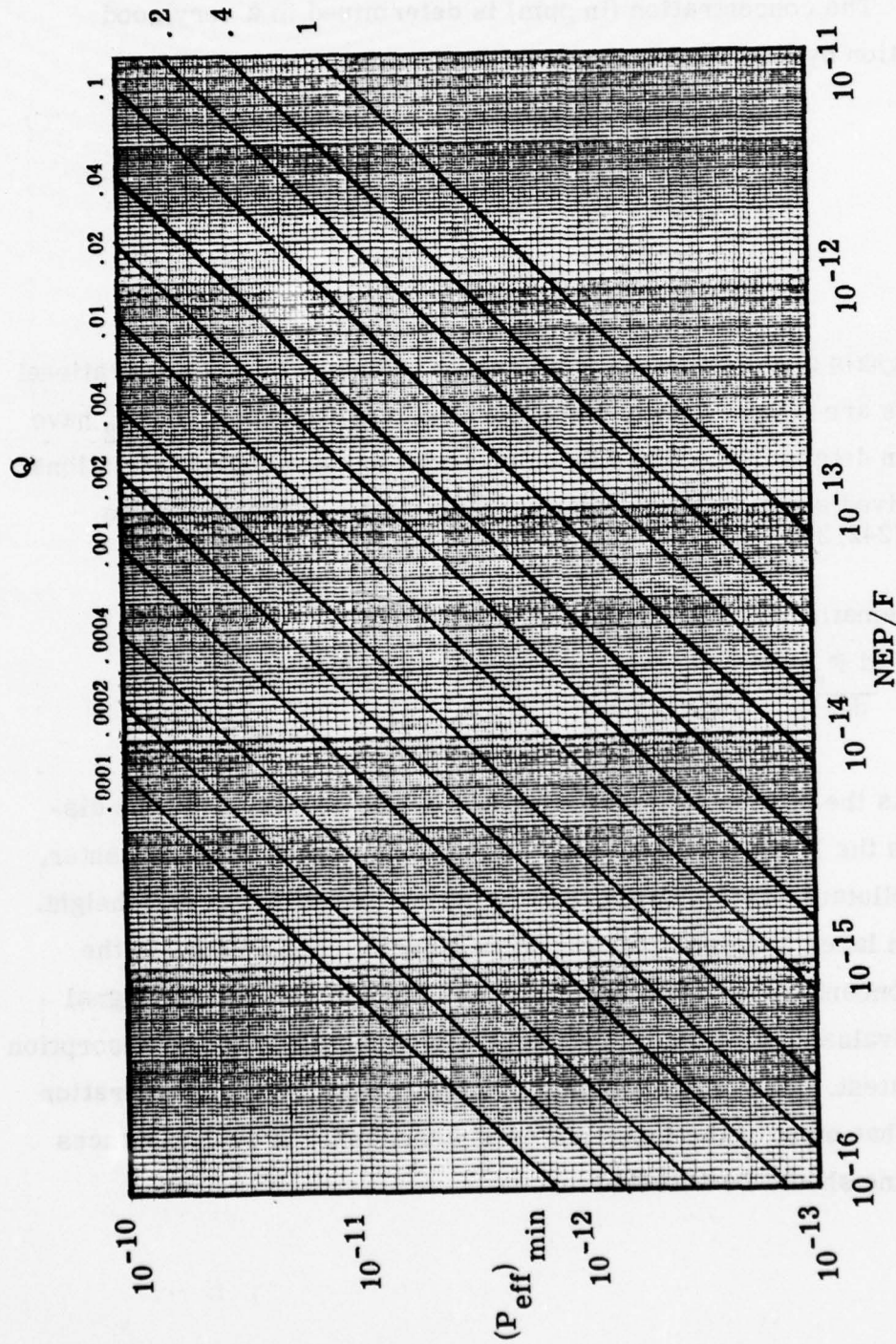


Figure 7. 3. 3-6. P_{eff} versus NEP/F for Different Values of Q .

7. 3. 3. 6 Data Analysis Procedures

The concentration (in ppm) is determined in a very good approximation by:

$$C(\text{ppm}) = \frac{\ln Q}{2 (k_1 - k_2) R}$$

where

$$Q = \frac{P(R)}{P'(R)}$$

The two signals are determined from analog signals. Because operational wavelengths are not yet known, the absorption coefficients k_1 and k_2 have not yet been determined. Since turbulence can introduce large variations in the received signals, the derivative/ratio signal method has been developed (242, 243).

Mathematically, this method is expressed as

$$\frac{1}{P_r} \frac{d P_r}{d \omega} = \frac{\delta P_r}{\delta k(\omega)} \frac{\delta k(\omega)}{\delta \omega} \frac{1}{P_r} = \frac{2 k_0 l (\omega - \omega_0) c}{\gamma^2 [1 + (\omega - \omega_0)^2 / \gamma^2]^2}$$

where k_0 is the absorption coefficient at the line center, l is the distance, ω is the laser frequency, ω_0 is the frequency at the line center, c is the pollutant concentration, and γ is the half-width at half-height. For a given laser frequency the signal is directly proportional to the pollutant concentration. For maximum sensitivity, the ratioed signal should be evaluated at a laser frequency where the slope of the absorption line is greatest. The only exception is when the pollutant concentration is so high that most of the laser power is absorbed. In such instances a weaker line should be selected.

The signal $[(dPr/d\omega)/Pr]$ as a function of pollutant concentration can be obtained from laboratory and/or field calibration. The calibration is made by using a gas cell with a known amount of pollutant gas. This can be done during the actual field test by observing the signal change after inserting the gas cell.

7. 3. 4 UV/Visible Long-Path with Laser Source

7. 3. 4. 1 Principle of Operation

The measurement principle of ultraviolet/visible (UV/Visible) long-path transmission is used to obtain line-averaged concentrations of SO_2 and NO_2 . Laser beams at two different wavelengths in the 2000-5000 Å region are emitted and the transmitted signals are recorded. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7. 3. 4. 2 System Description

The system consists of one or two lasers as transmitter, collecting optics which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical UV/visible long-path system is basically the same as was shown for the LWIR system in Figure 7. 3. 1-1, except that the IR detector is replaced by a photomultiplier or digicon tube. It should be noted that no prototype UV/visible long-path system using lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040.

7. 3. 4. 3 System Parameters

Commercially Available Lasers

N_2 Gas Laser

Xe Gas Laser

Neodymium Yag Solid State Laser

RDA Ruby

Dye Lasers

Other lasers that have transitions in the UV/visible region, but are not commercially available at present, include Ar, Cl, S, Kr, Ne, F, O₂, P, B, Pb, Si, Se, In, and I. (Refs. 265 and 257). Both CW and pulsed lasers may be used.

Operational Wavelengths

Have not been determined yet.

Laser Energy

For $2500 < \lambda < 4000 \text{ \AA}$, the maximum permissible laser energy is 10^{-3} W/cm^2 and for the visible spectrum, $4000 < \lambda < 7000 \text{ \AA}$, the laser energy is limited to 10^{-6} W/cm^2 .

Detector

Commercially available detectors are photomultipliers or digicons having response curves S-13 or S-19. These tubes are very sensitive and have low noise figures. In general, the UV/visible receivers become shot and/or background noise limited.

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (=A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below)

7. 3. 4. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a shot-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned} \ln Q^1 &= \ln \frac{P}{P'} \\ P_1 &= (G/R^2) e^{-2k_1 C R} \\ P' &= (G/R^2) e^{-2k_2 C R} \\ G &= \eta P_t A_o \Gamma(R) \\ \Gamma(R) &\approx 1/(\pi \Omega_L) \text{ for retroreflector} \\ \Gamma(R) &= \rho'/\pi \text{ for topographical reflector} \\ &\quad \text{(independent of } R \text{ if reflecting surface fills fov)} \\ dp &= (P_{\text{eff}} h\nu/\eta t)^{1/2} \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q}{2\pi} \left(\frac{\eta Q^t}{h\nu} P_{\text{eff}} \right)^{1/2}$$

where

$$Q = 2 \sum (k_1 - k_2)_i C_i R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: $G = \eta P_t A_o \Gamma(R)$

Assume: $P_t = 10^{-2} \text{ W}$ for 3000-4000 Å and 10^{-5} W for 4000-7000 Å, using 10 cm^2 laser beam area.

Result: Plot in Figure 7. 3. 4-1a and 1b shows G versus receiver aperture area A_o for five values of overall efficiency (optical and mechanical shutters) and $\Gamma(R)$.

Step 2: Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 3. 4-2 shows $\xi(R)$ versus R for the above values of kC.

Step 3: Calculate: $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m
 $\xi(R)$ for different values of G.

Result: Plot in Figure 7. 3. 4-3 shows P_{eff} versus $\xi(R)$ for various values of G.

Step 4: Calculate: Q for (a) SO_2 and (b) NO_2

Absorption coefficients of SO_2 and NO_2 for specific laser lines have not been determined yet. Actual calculation cannot be performed until data is available.

Result: Q versus C to be plotted in Figure 7. 3. 4-4 when available.

$$\eta \Gamma(R) = 1$$

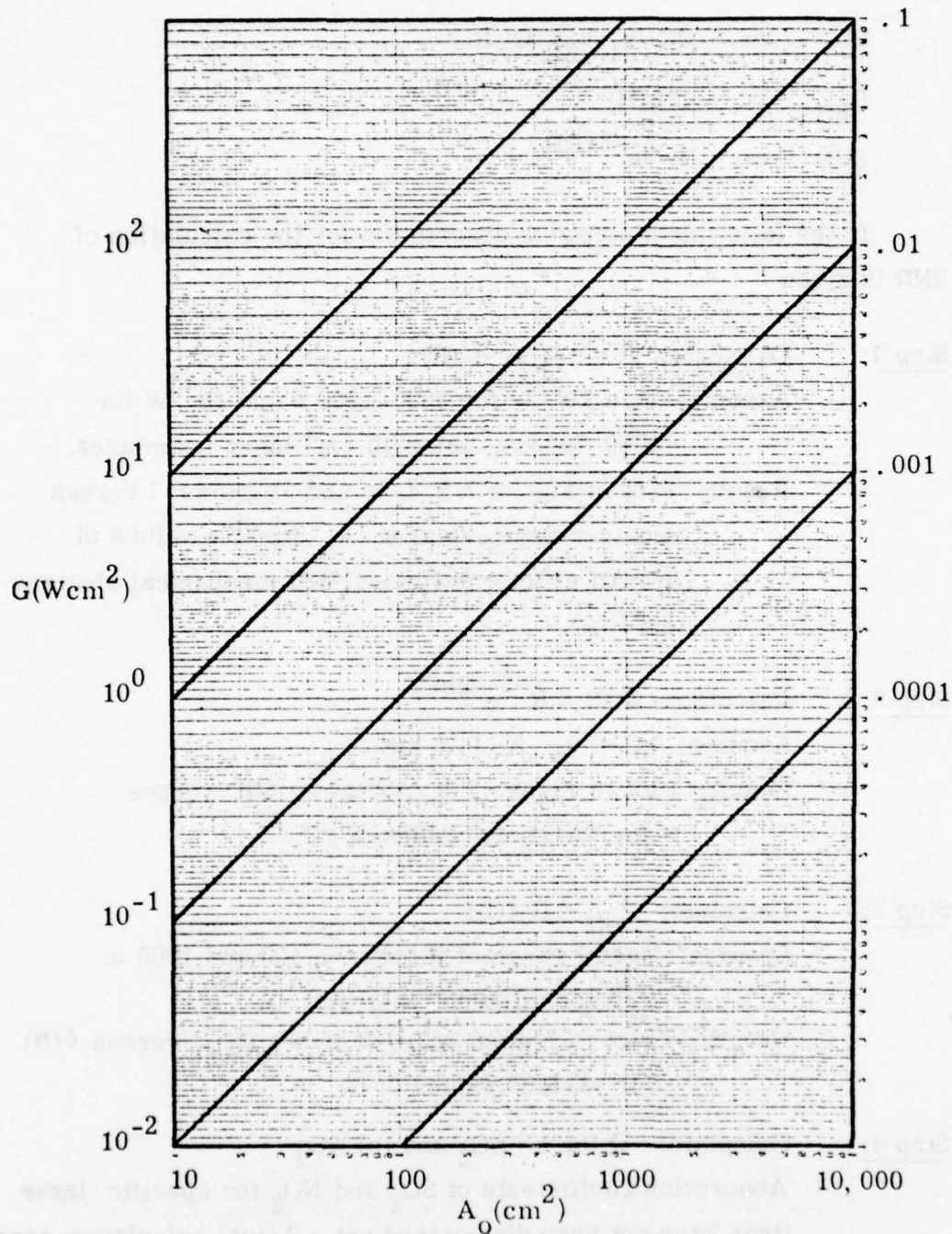


Figure 7. 3. 4- 1a. Function G versus A_0 for Five Values of $\eta \Gamma$, using 10^{-2}W for 10 cm^2 Laser Beam Area, Useful in Range 3000-4000 \AA .

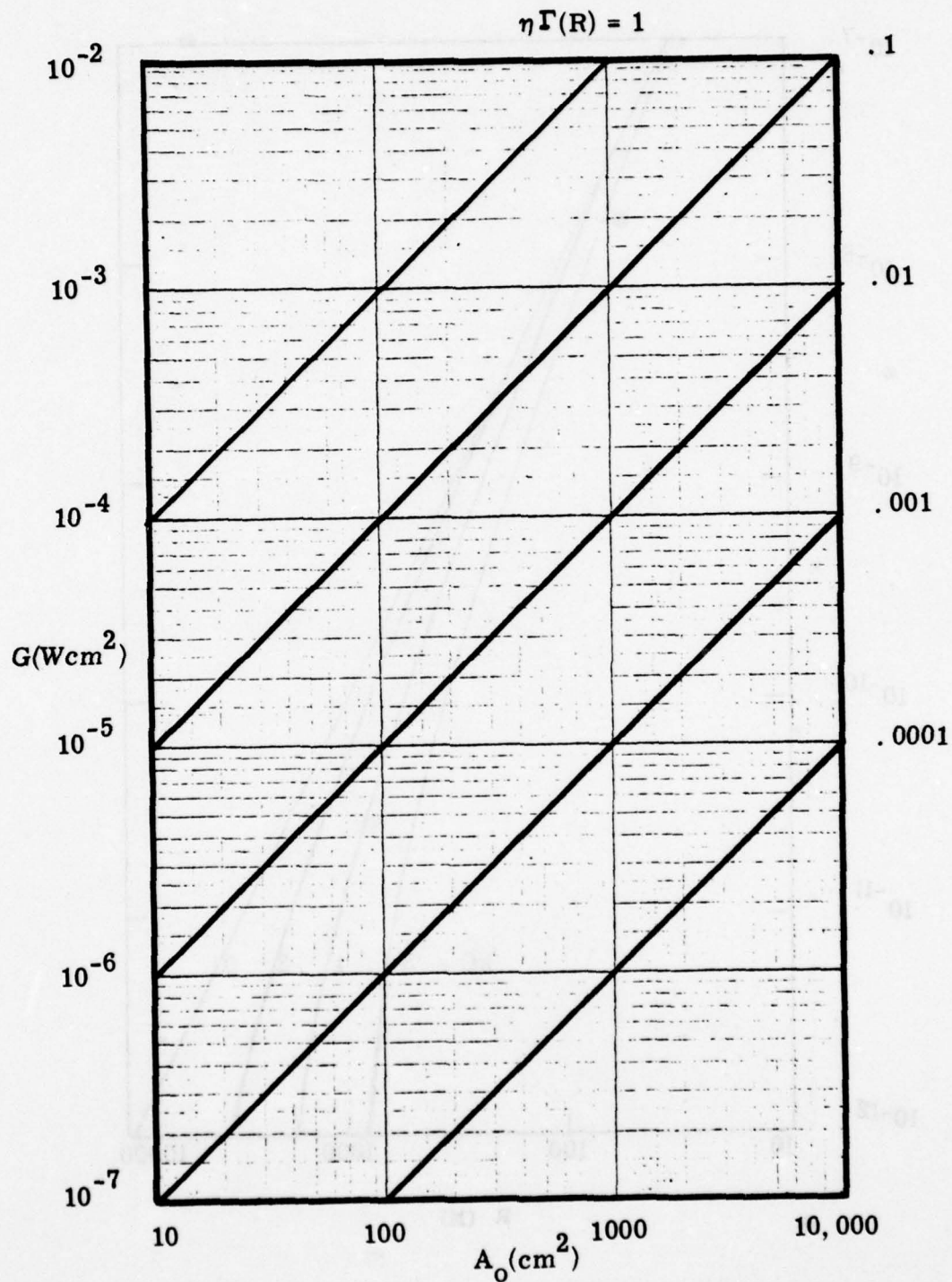


Figure 7.3.4-lb. Function G versus A_0 for Five Values of $\eta \Gamma$, using $P_t = 10^{-5}$ for 10 cm^2 Laser Beam Area, Useful in the Visible Region from 4000 to 7000 Å.

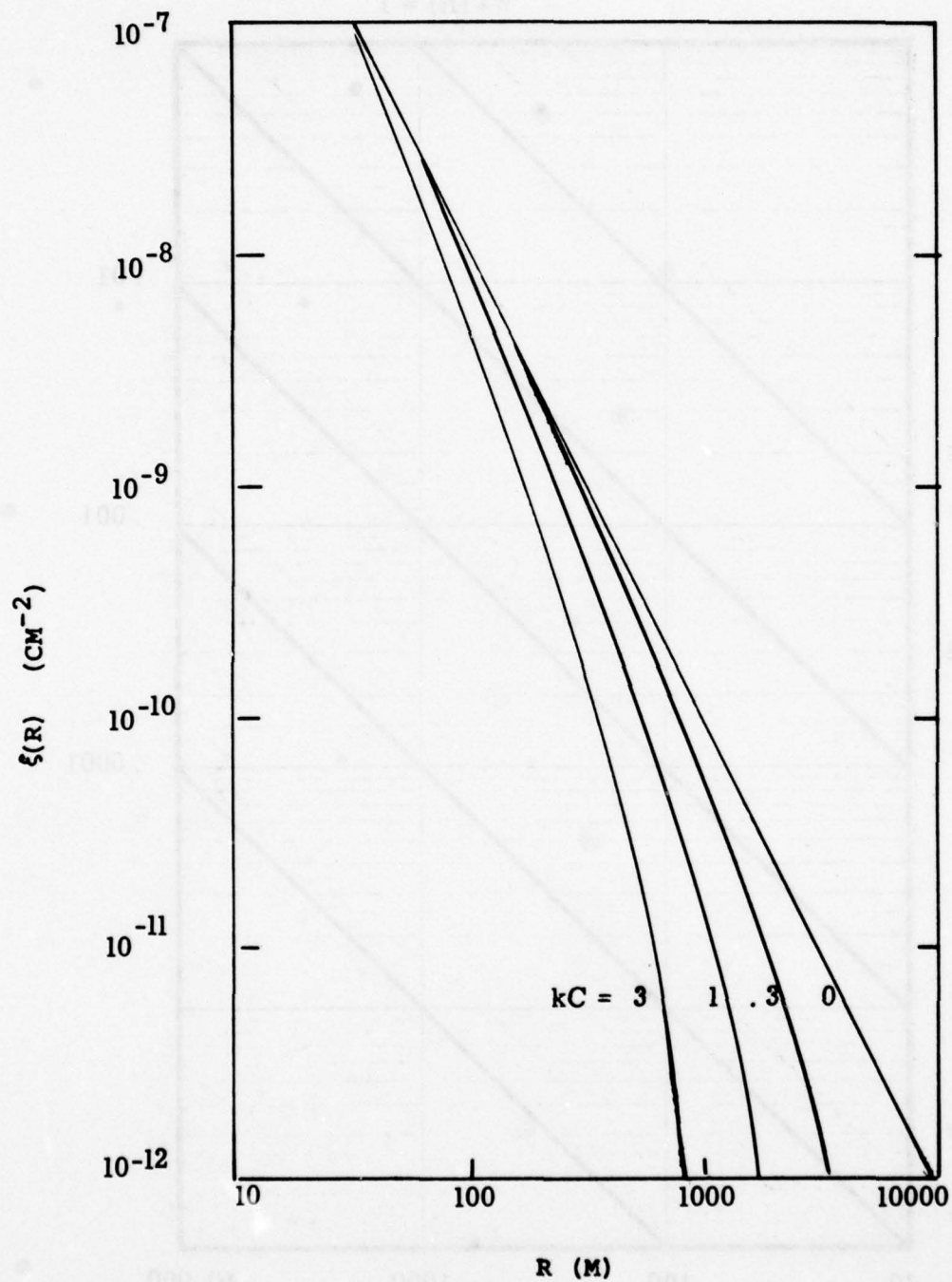


Figure 7.3.4.-2. Function $\xi(R)$ vs. Range for Different Values of kC (KM^{-1})

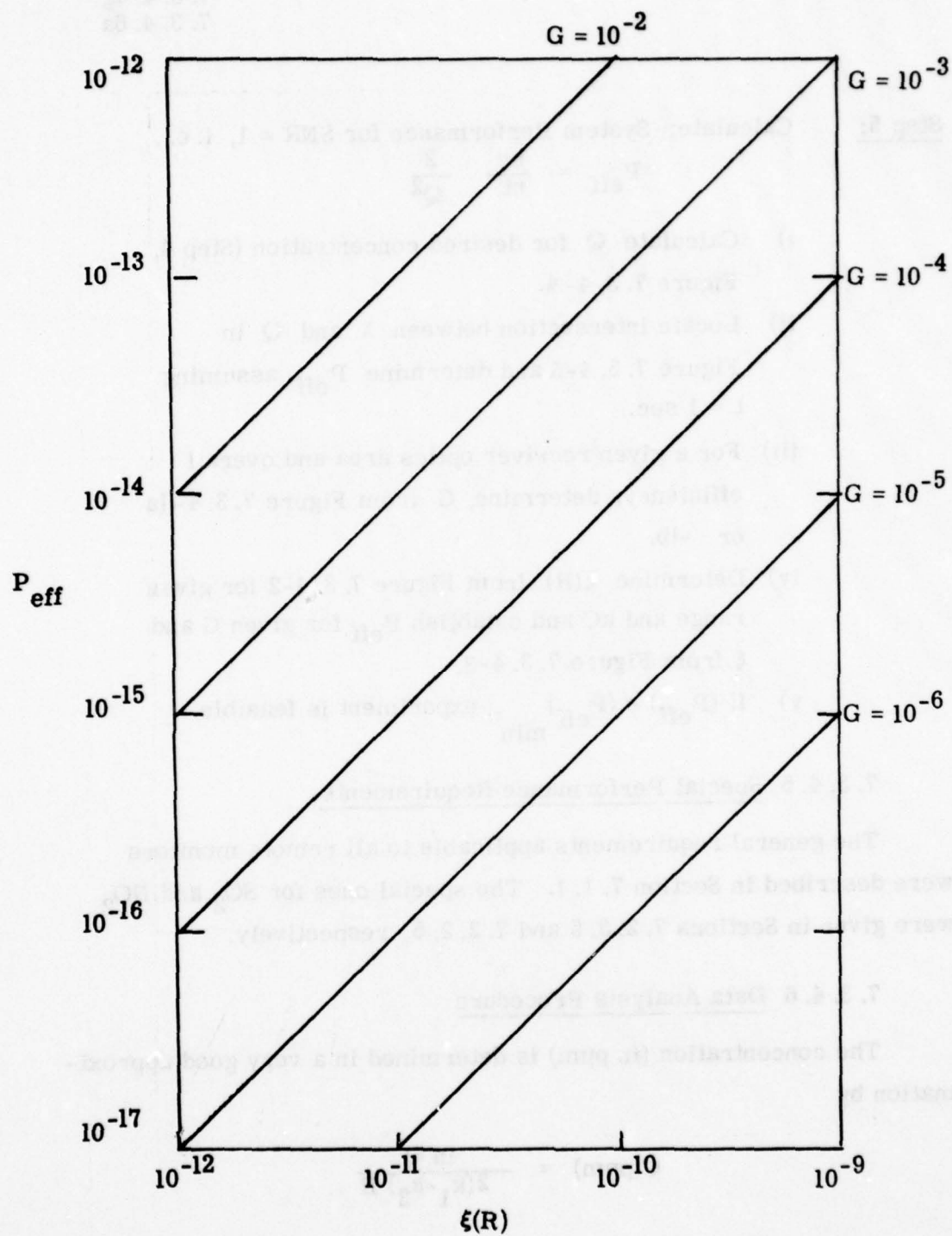


Figure 7. 3. 4-3. P_{eff} versus the Function $\xi(R)$ for Different Values of G .

Step 5: Calculate: System Performance for SNR = 1, i. e. ,

$$P_{\text{eff}} = \frac{h\nu}{\eta t} \frac{2}{Q^2}$$

- i) Calculate Q for desired concentration (Step 4, Figure 7. 3. 4-4.
- ii) Locate intersection between λ and Q in Figure 7. 3. 4-5 and determine P_{eff} assuming $t = 1$ sec.
- iii) For a given receiver optics area and overall efficiency, determine G from Figure 7. 3. 4-1a or -1b.
- iv) Determine $\xi(R)$ from Figure 7. 3. 4-2 for given range and kC and establish P_{eff} for given G and ξ from Figure 7. 3. 4-3.
- v) If $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$, experiment is feasible.

7. 3. 4. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. The special ones for SO_2 and NO_2 were given in Sections 7. 2. 3. 5 and 7. 2. 2. 5, respectively.

7. 3. 4. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{\ln Q}{2(k_1 - k_2) R}$$

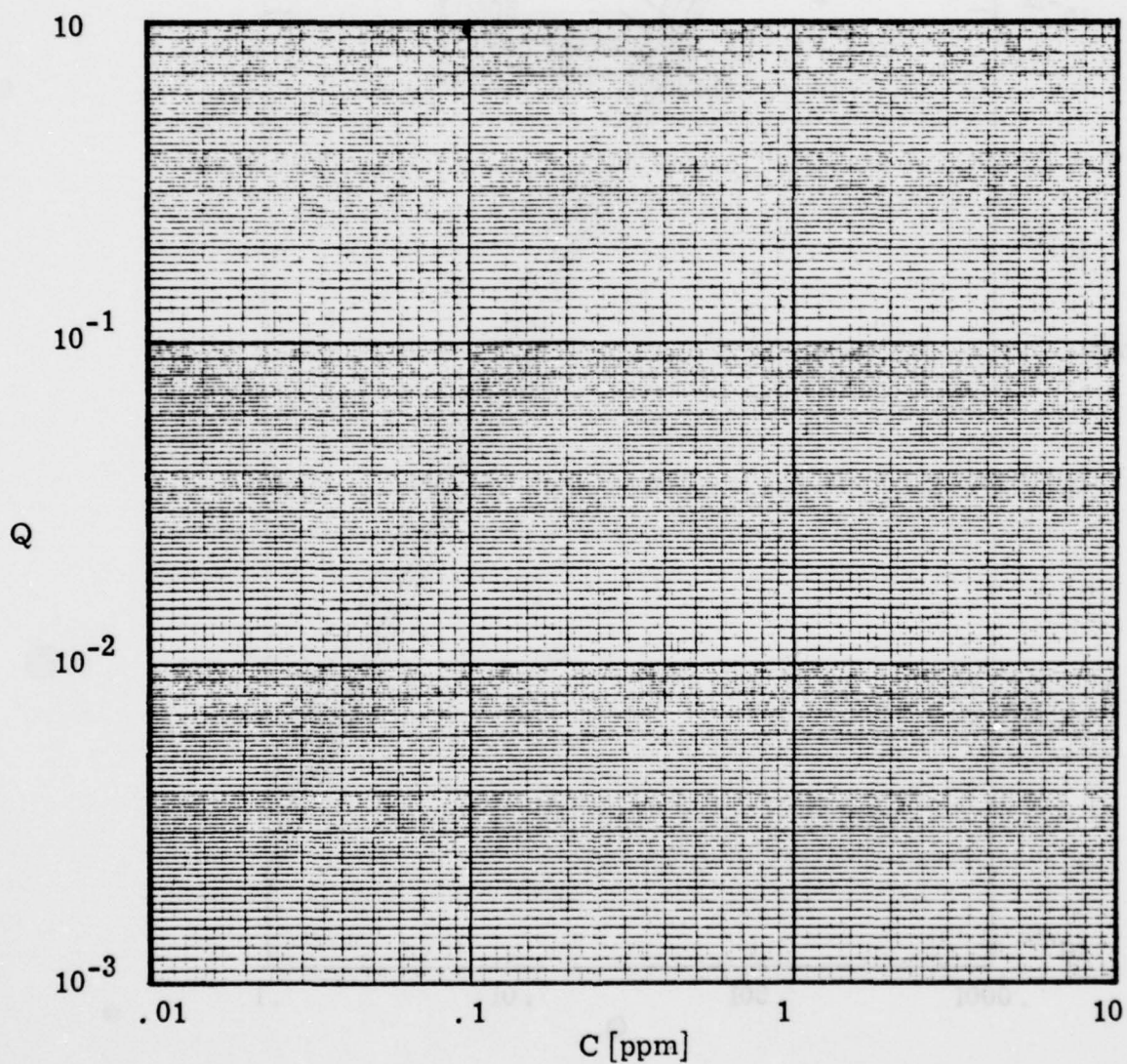


Figure 7.3. 4-4. Q versus Concentration of SO_2 and NO_2 for a Resolution Element of 15 m.
See Step 4, Data required for this graph is not yet determined.

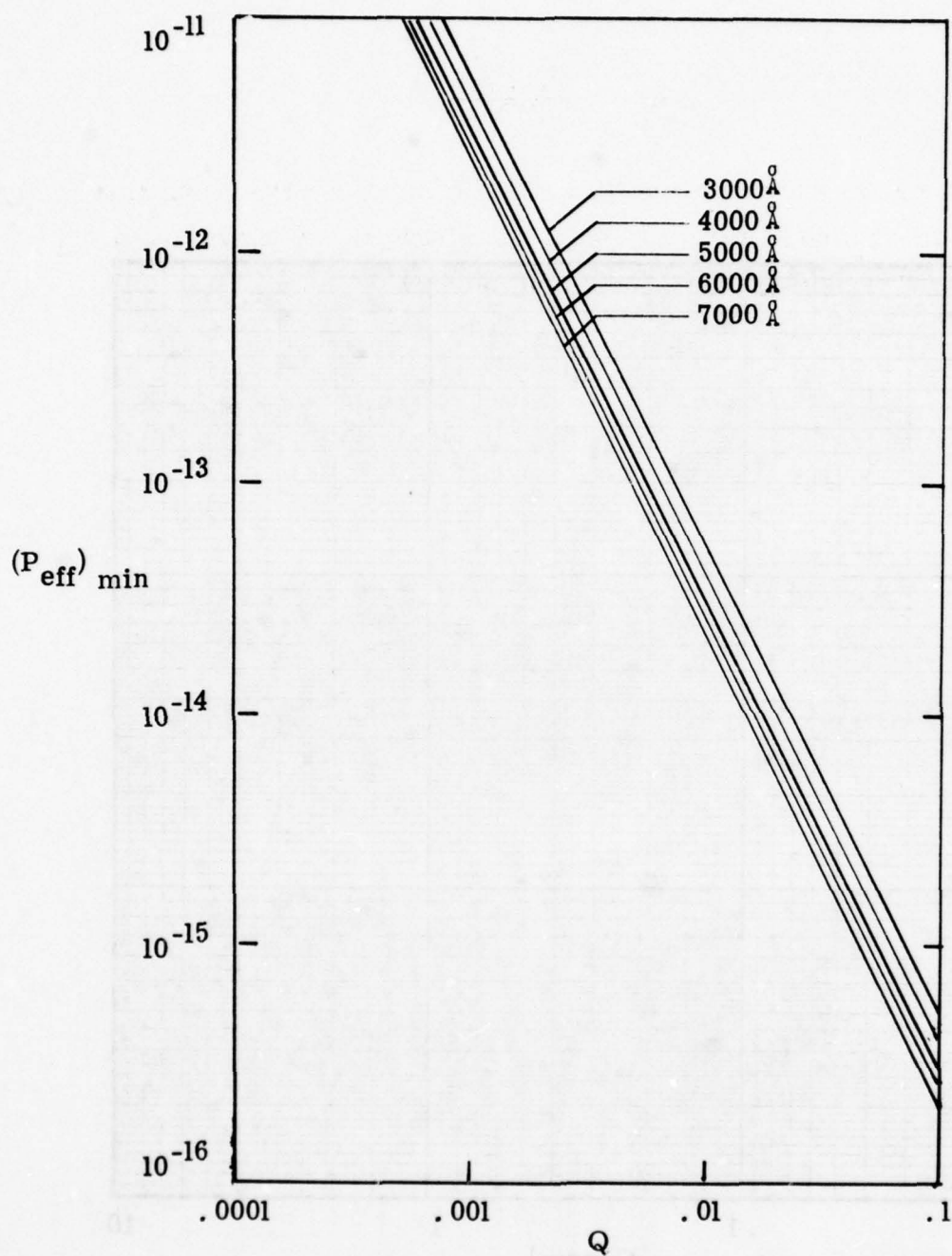


Figure 7. 3. 4-5. P_{eff} versus Q for $3000 < \lambda < 7000 \text{ \AA}$,
Assuming an Integration Time of .5
sec and a Quantum Efficiency of 50%.

where

$$Q = \frac{P(R)}{P(R)}$$

The two signals are determined from analog signals. The absorption coefficients k_1 and k_2 have not been determined yet, because the exact operational wavelengths are not yet established.

7.3.5 IR Long-Path with Broadband Source and Dispersive Receiver

7.3.5.1 Principle of Operation

The measurement principle of the infrared long-path transmission is used to obtain line averaged concentrations of all gaseous pollutants of interest to NAAQS. A beam from a broadband source is emitted and the received signals are recorded by the tunable receiver as a function of wavelength. By differencing the signals on and off the pollutant lines, the average absorption of the pollutants over the line-of-sight can be determined. The concentration of the pollutant is proportional to the logarithm of the transmission. The proportionality factor is the absorption coefficient which must be known.

7.3.5.2 System Description

The system consists of a broadband source, such as a blackbody, collecting optics and receiver consisting of a tunable spectrometer, electronics and data display. A block diagram indicating the essential elements of a typical system is shown in Figure 7.3.5-1. Two different kinds of spectrophotometers are shown in Figure 7.3.5-2.

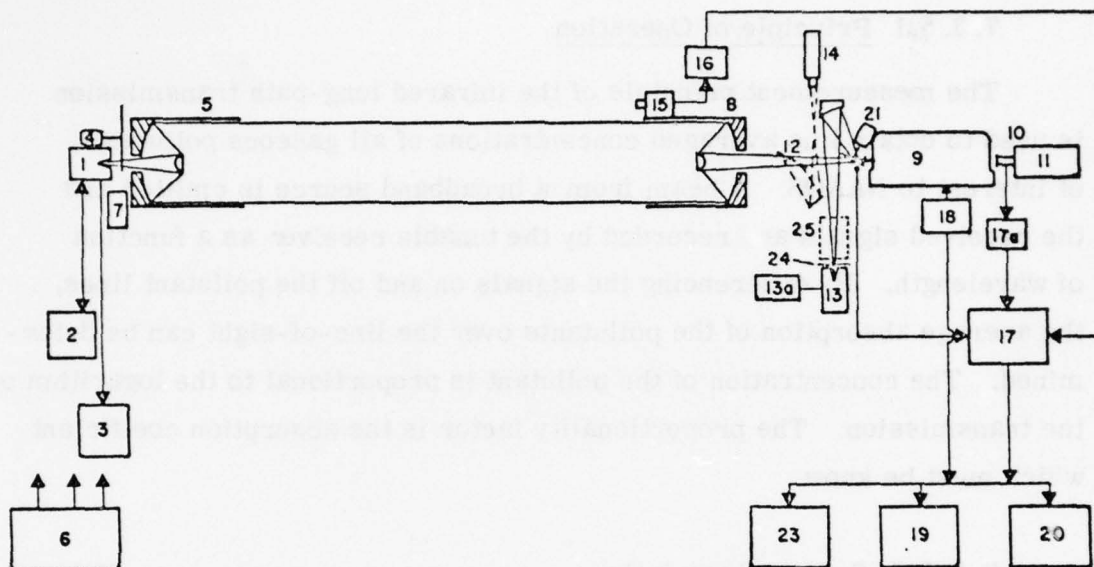
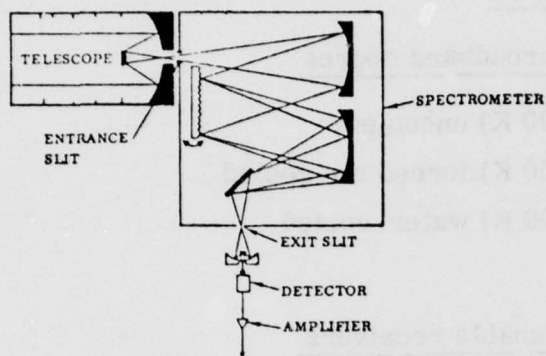
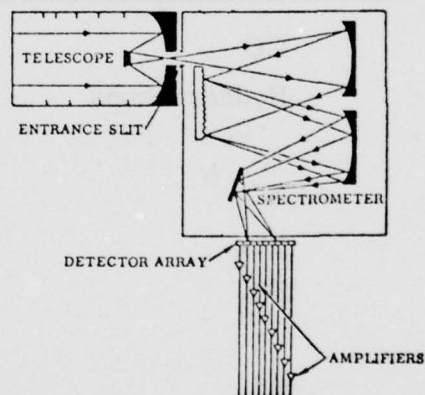


Figure 7. 3. 5-1. Schematic of a Long-Path Monitor, Using a Blackbody as Illuminator Adopted from Ref. 165. The Components are:

- | | |
|-----------------------------------|------------------------------|
| 1. Blackbody | 13a. Temperature Controller |
| 2. Temperature Controller | 14. Telescope |
| 3. Continuous Temperature Readout | 15. InAs Detector |
| 4. Chopper | 16. Preamplifier |
| 5. Source Optics | 17. Amplifying System |
| 6. Power Generator | 17a. Preamplifier |
| 7. Boresight Microscope | 18. Wavelength Drive |
| 8. Receiver Optics | 19. DVM-Digital Readout |
| 9. Spectrometer | 20. Strip Chart Recorder |
| 10. Ge:Hg Detector | 21. Chopper |
| 11. Mechanical Cooler | 22. Power Supply (not shown) |
| 12. 2 Position Mirror | 23. Magnetic Tape |
| 13. Calibration Blackbody | 24. Precision Aperture |
| | 25. Gas Cell |



Monochromator



Polychromator

Figure 7. 3. 5-2. Two Different Kinds of Tunable Receivers Using a Dispersive Element (Grating).

7. 3. 5. 3 System ParametersCommercially available broadband source

Blackbody (~ 1200 K) uncooled
 (~ 1500 K) forced air cooled
 (~ 1800 K) water-cooled
 Nernst glower

Commercially available tunable receivers

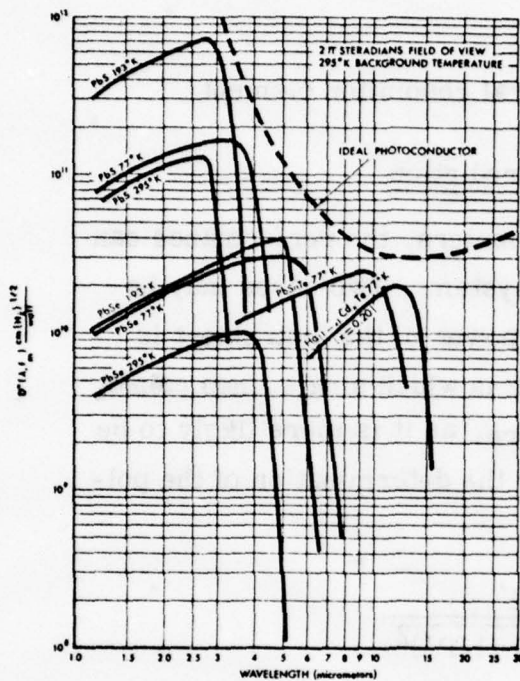
Monochromator (single and double pass)
 Polychromator

Operational wavelength regions

CO	4.5 - 4.8 μm
Hydrocarbons	3.0 - 4.0 μm 9.5 - 12.0 μm
NO	5.1 - 5.5 μm
NO ₂	3.3 - 3.6 μm
SO ₂	3.95 - 4.05 μm 8.4 - 9.0 μm
O ₃	9.4 - 9.8 μm

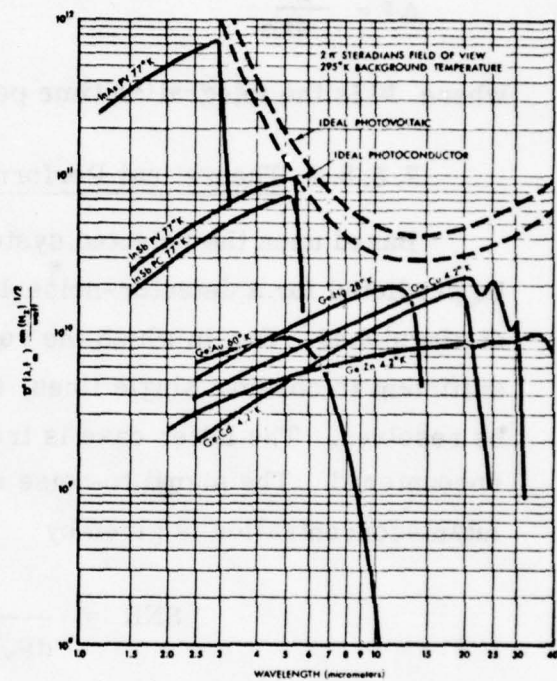
Detector

Commercially available detectors in the infrared are shown in the following graphs (Figures 7. 3. 5-3a and -3b):



SPECTRAL DETECTIVITIES FOR ABOVE-AVERAGE DETECTORS FABRICATED BY SIRC.
A REDUCTION IN BACKGROUND PHOTON FLUX PRODUCES HIGHER DETECTIVITIES

Figure 7. 3. 5-3a



SPECTRAL DETECTIVITIES FOR ABOVE-AVERAGE DETECTORS FABRICATED BY SIRC.
A REDUCTION IN BACKGROUND PHOTON FLUX PRODUCES HIGHER DETECTIVITIES

Figure 7. 3. 5-3b

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η_{opt}
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (shown in the following).

Electronic Bandpass

$$\Delta f = \frac{1}{4tc}$$

where t_c is the integration time per spectral resolution element.

7.3.5.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. Two cases may be distinguished. One in which the resolving power of the instrument is sufficient to observe single lines, the other in which single lines cannot be resolved. The latter case is treated here, as it is more likely to be encountered. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$SNR = \frac{\ln Q'}{dP\sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\ln Q = \ln P/P'$$

$$P = G/R^2 e^{-(w/d)_1} \Delta\lambda$$

$$P' = G/R^2 e^{-(w/d)_2} \Delta\lambda$$

$$G = \eta A^2 N^0(\lambda, T)$$

$$w/d = kCR(1+kCR/4a)^{-1/2}$$

$$dP = NEP = (A_d/4t_c)^{1/2}/D^*$$

For these expressions, w/d is the line width to line spacing ratio.

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2 \text{NEP}}}$$

where

$$Q = (w/d)_2 - (w/d)_1$$

$$P_{\text{eff}} = G \xi(R) \Delta \lambda$$

$$\xi(R) = R^{-2} e^{-(w/d)}$$

In the following a stepwise description for the calculation of SNR is given

Step 1:

Calculate: NEP

Assume: $D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ (representative for MWIR to LWIR)

$D^* = 3 \times 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ (representative for SWIR)

Result: Plot in Figure 7. 3. 5-4 shows NEP versus A_d for different integration times.

Step 2:

Calculate: G

Assume: $T = 1600 \text{ K}$

$\eta = .1$

Result: Plot in Figure 7. 3. 5-5 shows G versus λ for different values of A_0 .

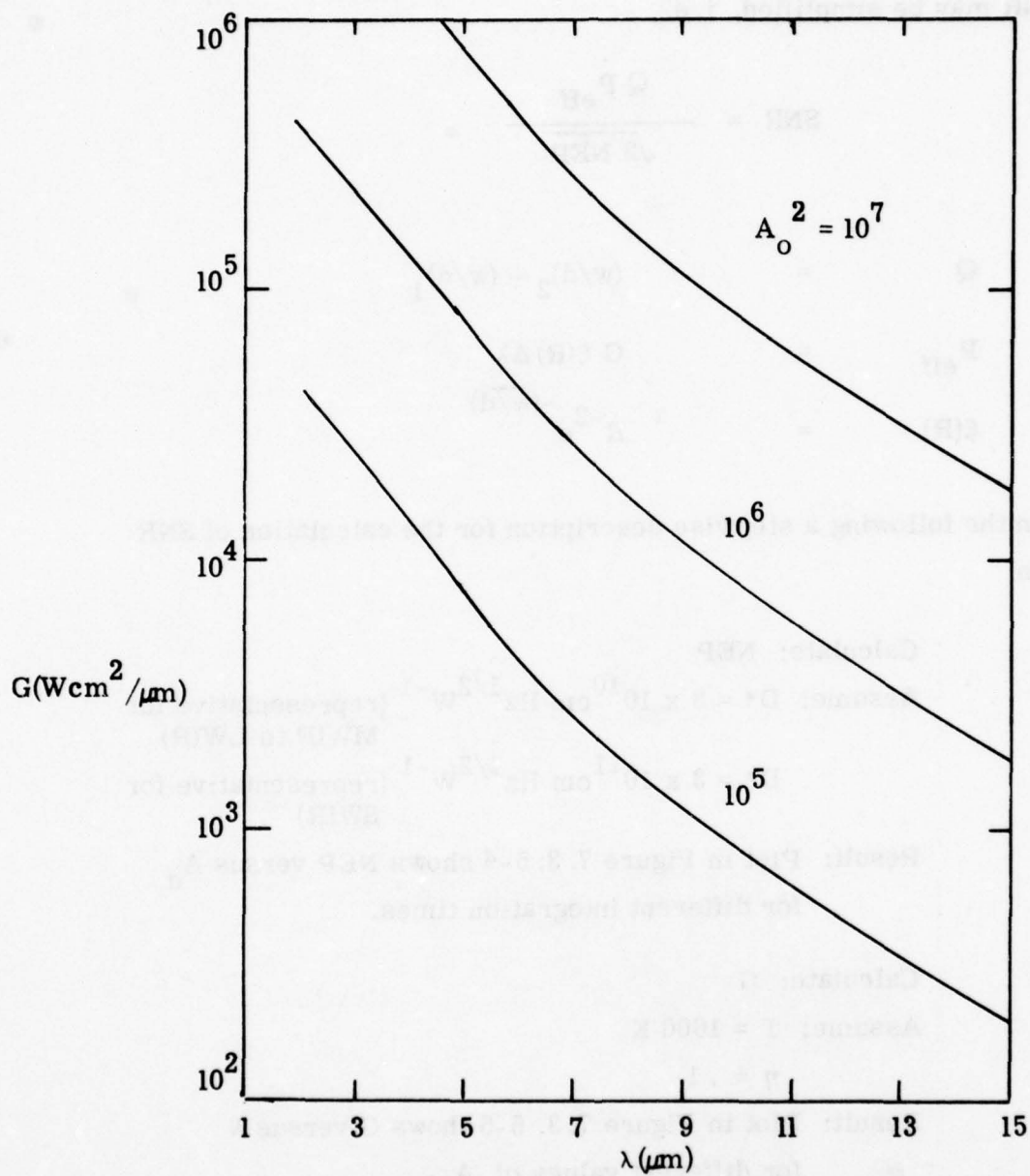


Figure 7.3.5-5. G versus λ for Three Different Values of A_0

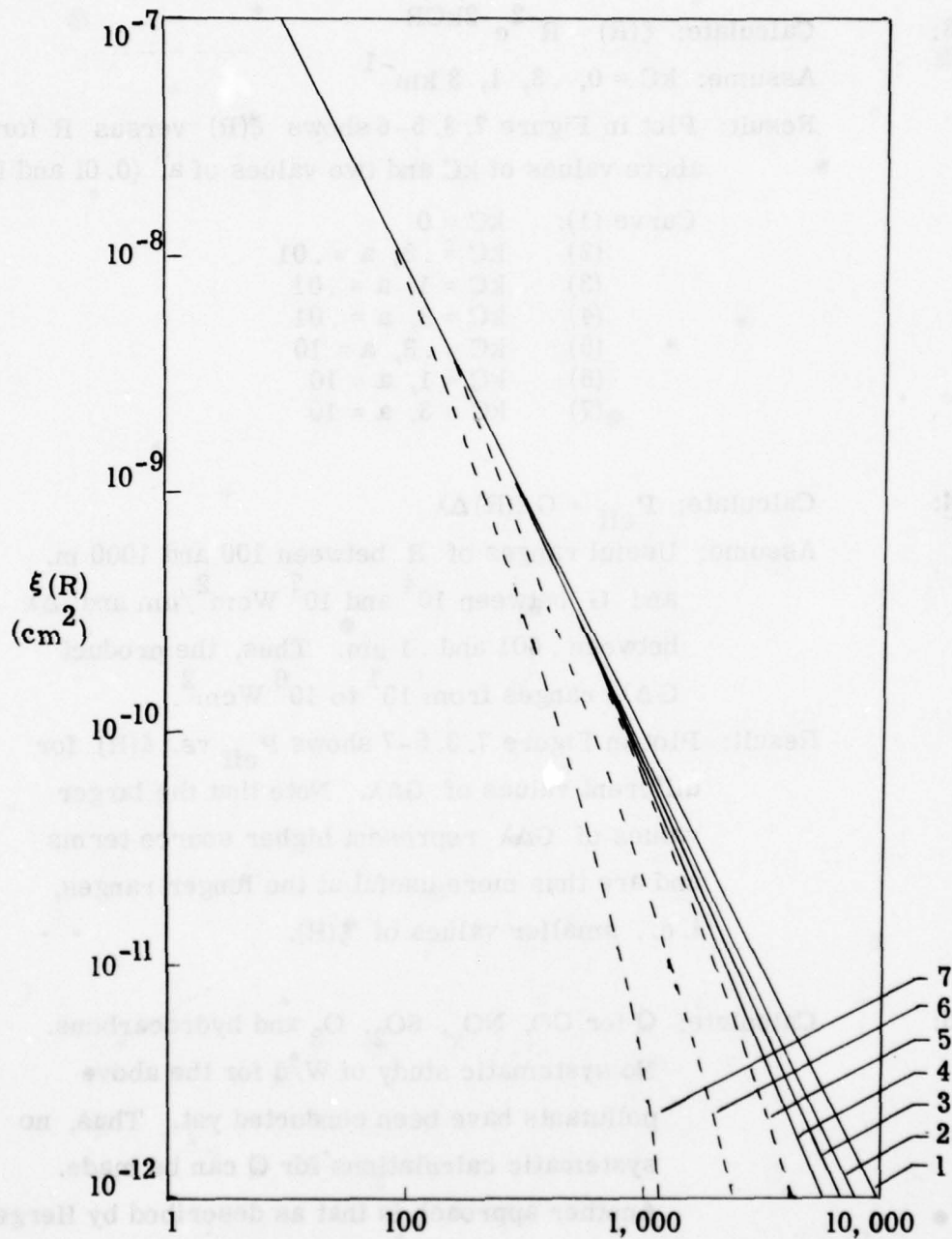


Figure 7.3.5-6. $\xi(R)$ versus R for Different Values

of kC and a : Curve (1) $kC = 0$;

Curve (2) $kC = .3$, $a = .01$

(3) $kC = 1$, $a = .01$

(4) $kC = 3$, $a = .01$

(5) $kC = .3$, $a = 10$

(6) $kC = 1$, $a = 10$

(7) $kC = 3$, $a = 10$

Step 3:

Calculate: $\xi(R) = R^{-2} e^{-2kCR}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 3. 5-6 shows $\xi(R)$ versus R for the above values of kC and two values of a . (0.01 and 10).

- Curve (1): $kC = 0$
 (2) $kC = .3, a = .01$
 (3) $kC = 1, a = .01$
 (4) $kC = 3, a = .01$
 (5) $kC = .3, a = 10$
 (6) $kC = 1, a = 10$
 (7) $kC = 3, a = 10$

Step 4:

Calculate: $P_{\text{eff}} = G \xi(R) \Delta\lambda$

Assume: Useful ranges of R between 100 and 1000 m, and G between 10^4 and $10^7 \text{ Wcm}^2/\mu\text{m}$ and $\Delta\lambda$ between .001 and .1 μm . Thus, the product $G\Delta\lambda$ ranges from 10^1 to 10^6 Wcm^2 .

Result: Plot in Figure 7. 3. 5-7 shows P_{eff} vs. $\xi(R)$ for different values of $G\Delta\lambda$. Note that the larger values of $G\Delta\lambda$ represent higher source terms and are thus more useful at the longer ranges, i. e., smaller values of $\xi(R)$.

Step 5:

Calculate: Q for CO , NO_x , SO_2 , O_3 and hydrocarbons.

No systematic study of W/d for the above pollutants have been conducted yet. Thus, no systematic calculations for Q can be made.

Another approach is that as described by Herget⁽²⁴⁶⁾, whereby the signals obtained from the absorption of the pollutant in an absorption cell is related to the signal obtained in the field (see Section 5. 3. 2. 2).

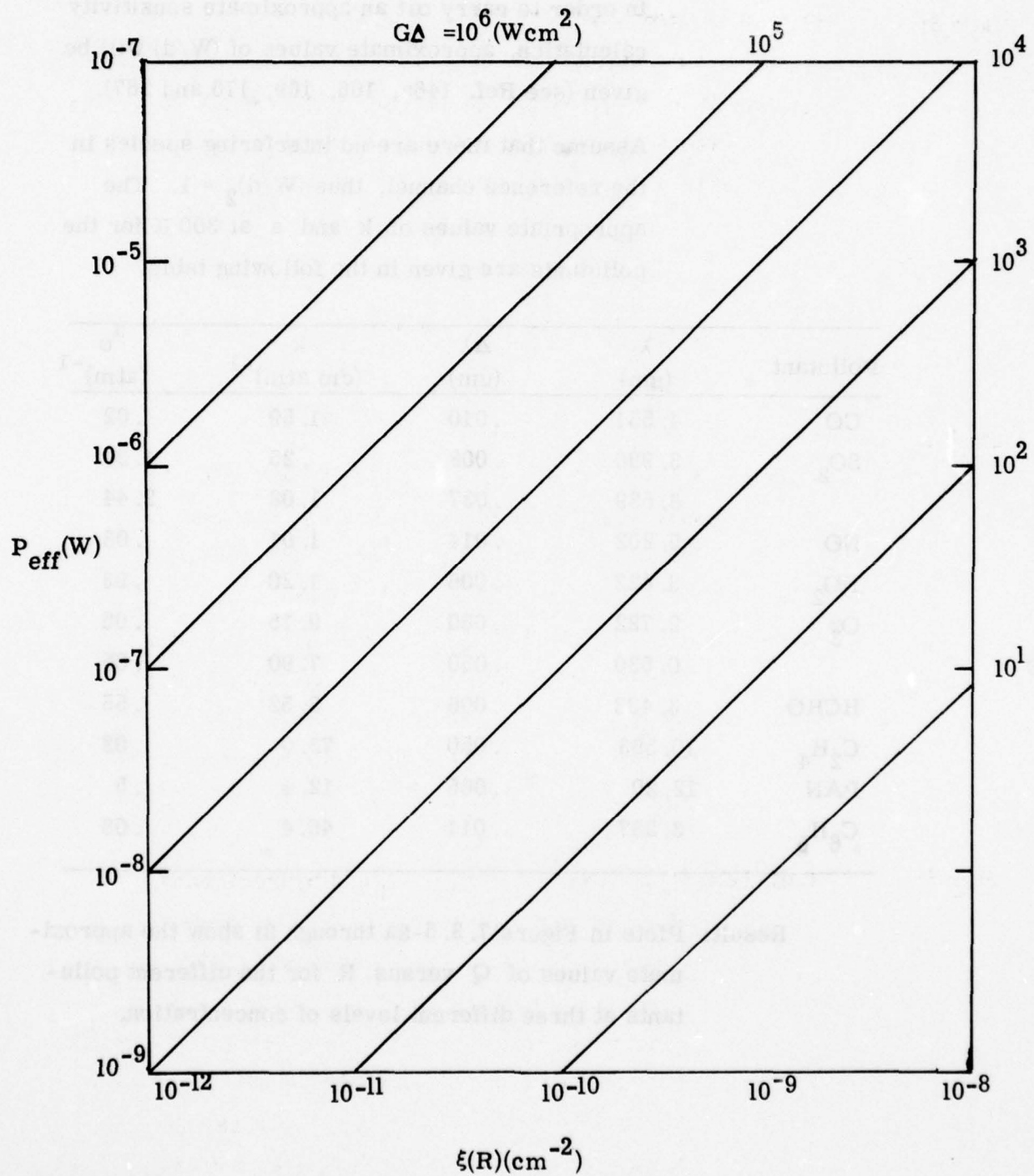


Figure 7. 3. 5-7. P_{eff} versus $\xi(R)$ for Different Values of $G\Delta\lambda$.

In order to carry out an approximate sensitivity calculation, approximate values of (W/d) will be given (see Ref. 146a, 166, 169, 176 and 267).

Assume that there are no interfering species in the reference channel, thus $(W/d)_2 = 1$. The appropriate values of k and a at 300 K for the pollutants are given in the following table.

Pollutant	λ (μm)	$\Delta\lambda$ (μm)	k (cm atm) ⁻¹	a_o (atm) ⁻¹
CO	4.551	.010	1.59	.02
SO ₂	3.996	.008	.25	1.39
	8.639	.037	1.08	2.44
NO	5.202	.014	1.01	.08
NO ₂	3.422	.006	1.20	.93
O ₃	9.722	.060	9.15	.05
	0.530	.050	7.90	.05
HCHO	3.433	.006	3.52	.55
C ₂ H ₄	10.563	.050	73.0	.03
PAN	12.20	.065	12.4	.5
C ₆ H ₆	3.287	.011	46.4	.08

Result: Plots in Figure 7.3.5-8a through 8i show the approximate values of Q versus R for the different pollutants at three different levels of concentration.

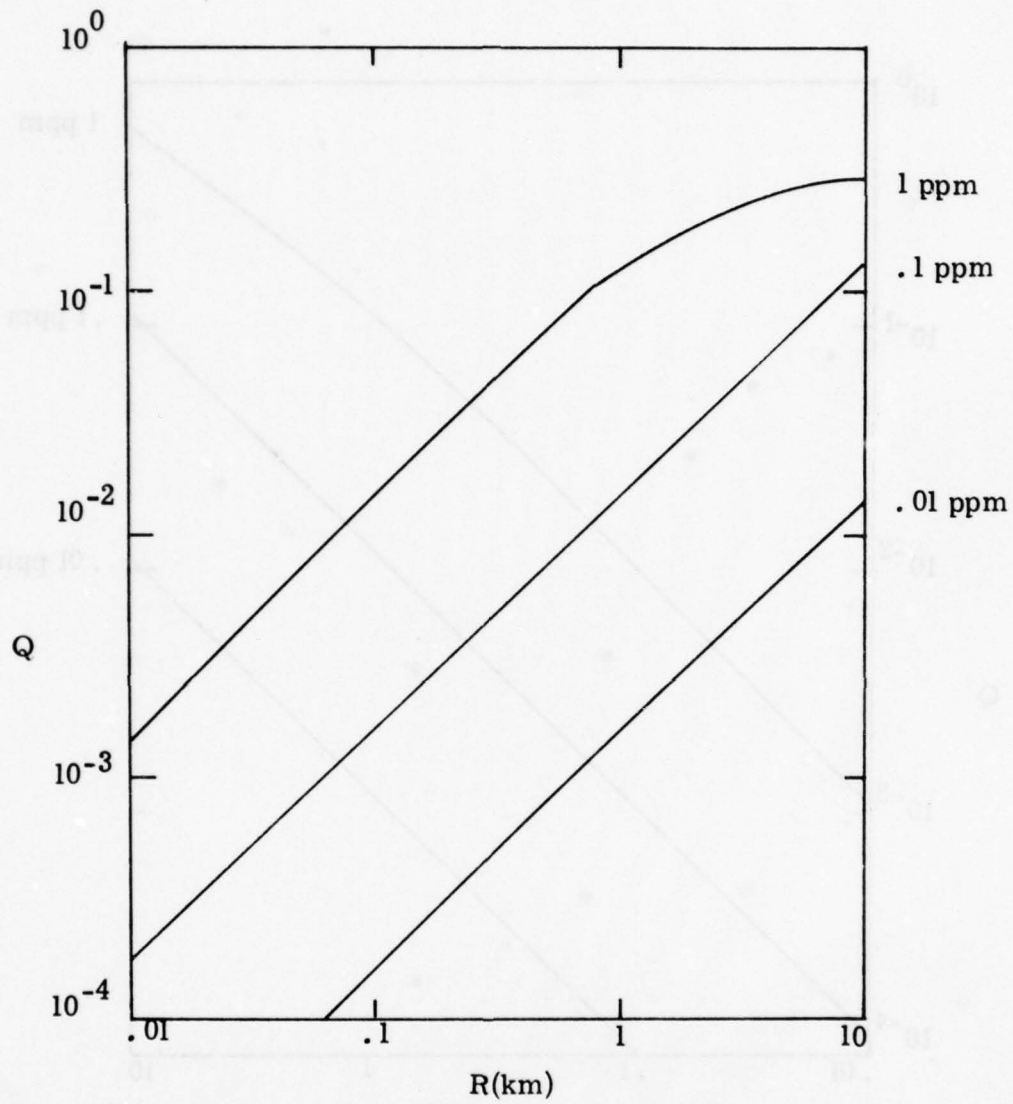


Figure 7. 3. 5-8a. Q for CO versus range for three levels of concentration.

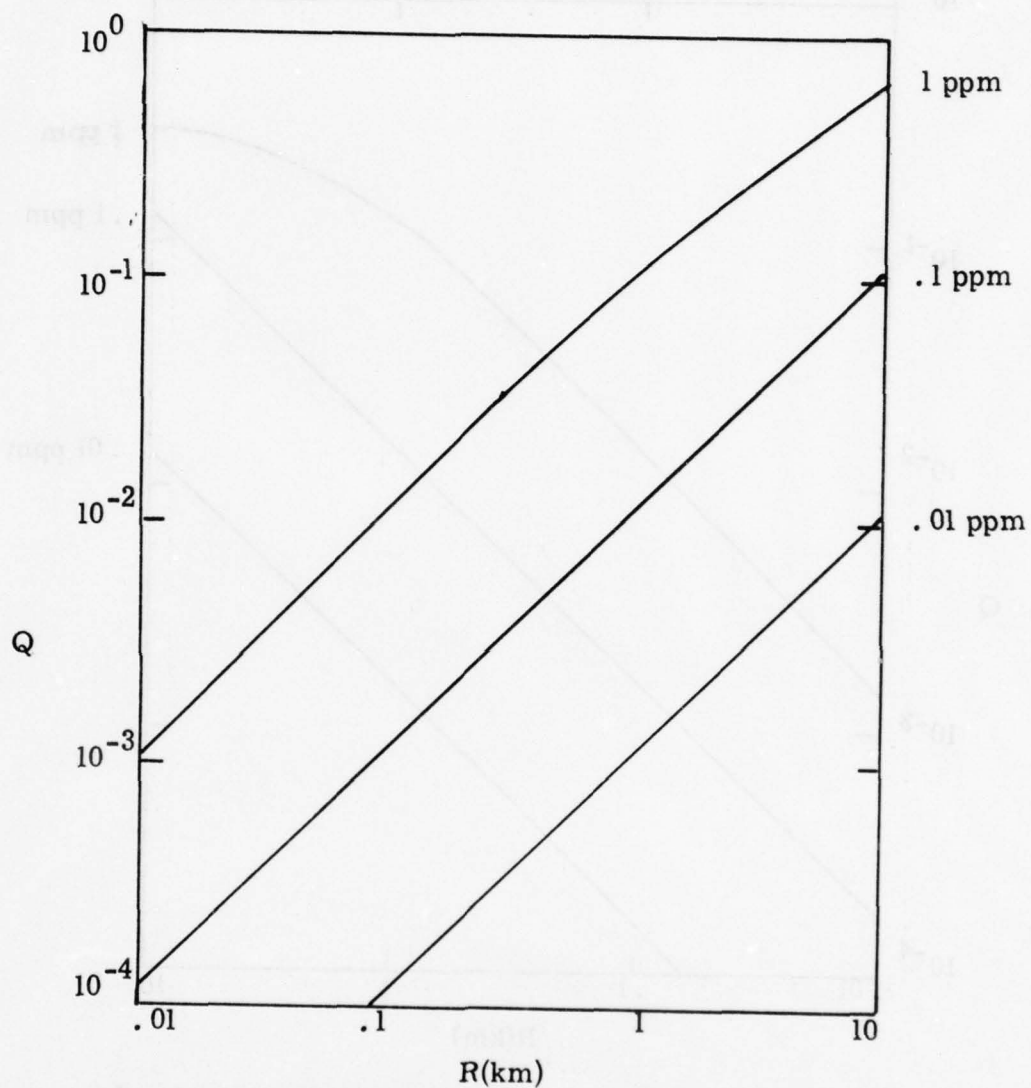


Figure 7. 3. 5-8b Q for SO_2 versus range for three levels of concentration .

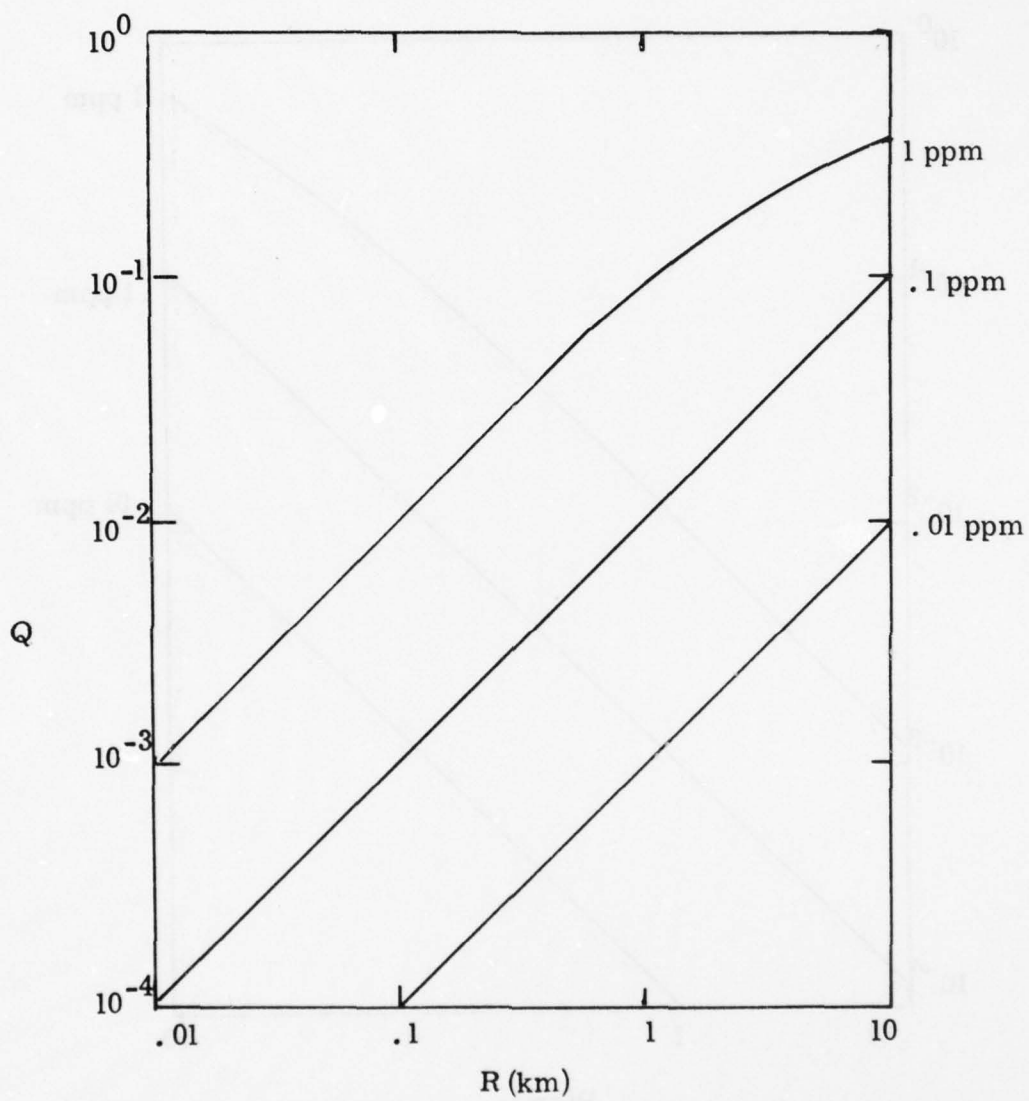


Figure 7.3.5-8c. Q for NO versus range for three levels of concentration.

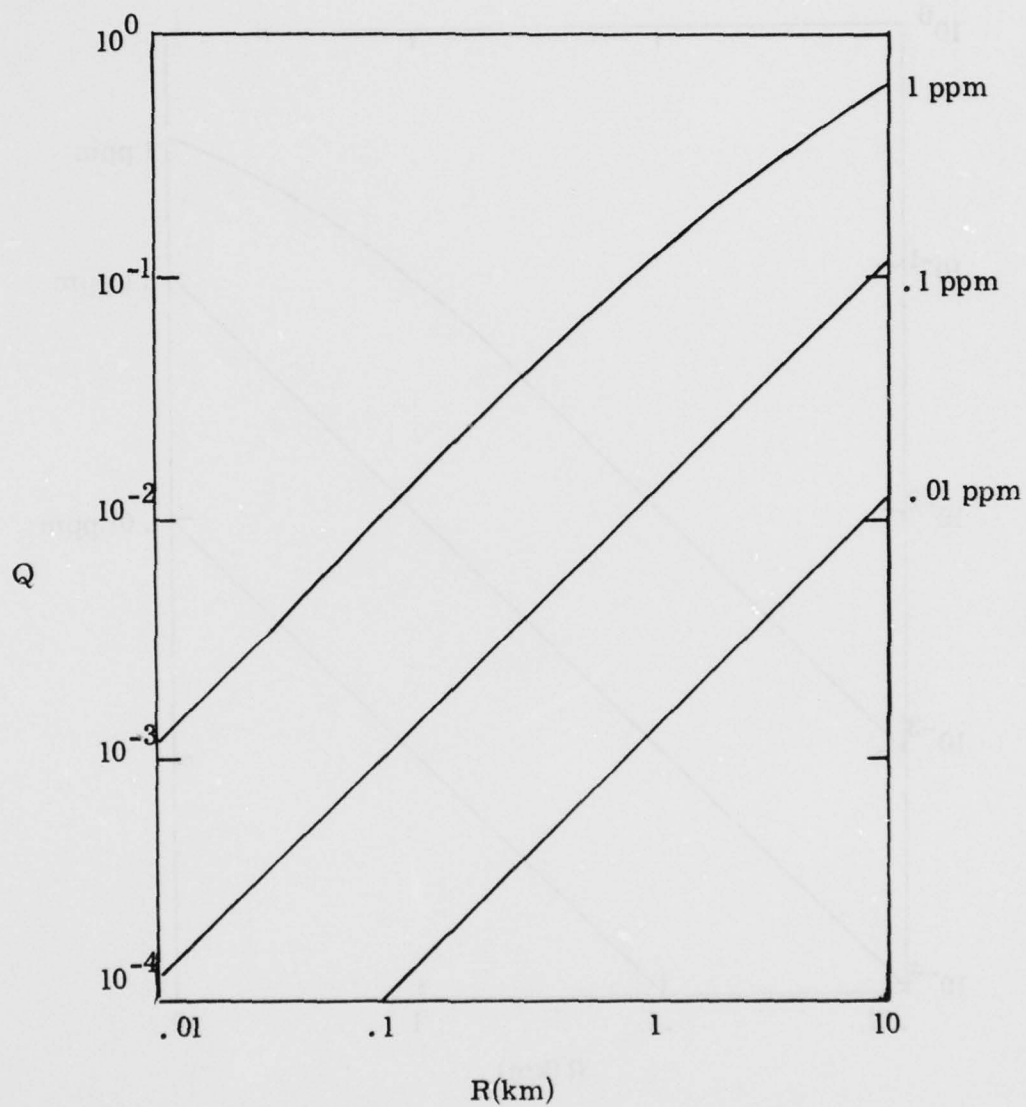


Figure 7. 3. 5-8d. Q for NO_2 versus range for three levels of concentration.

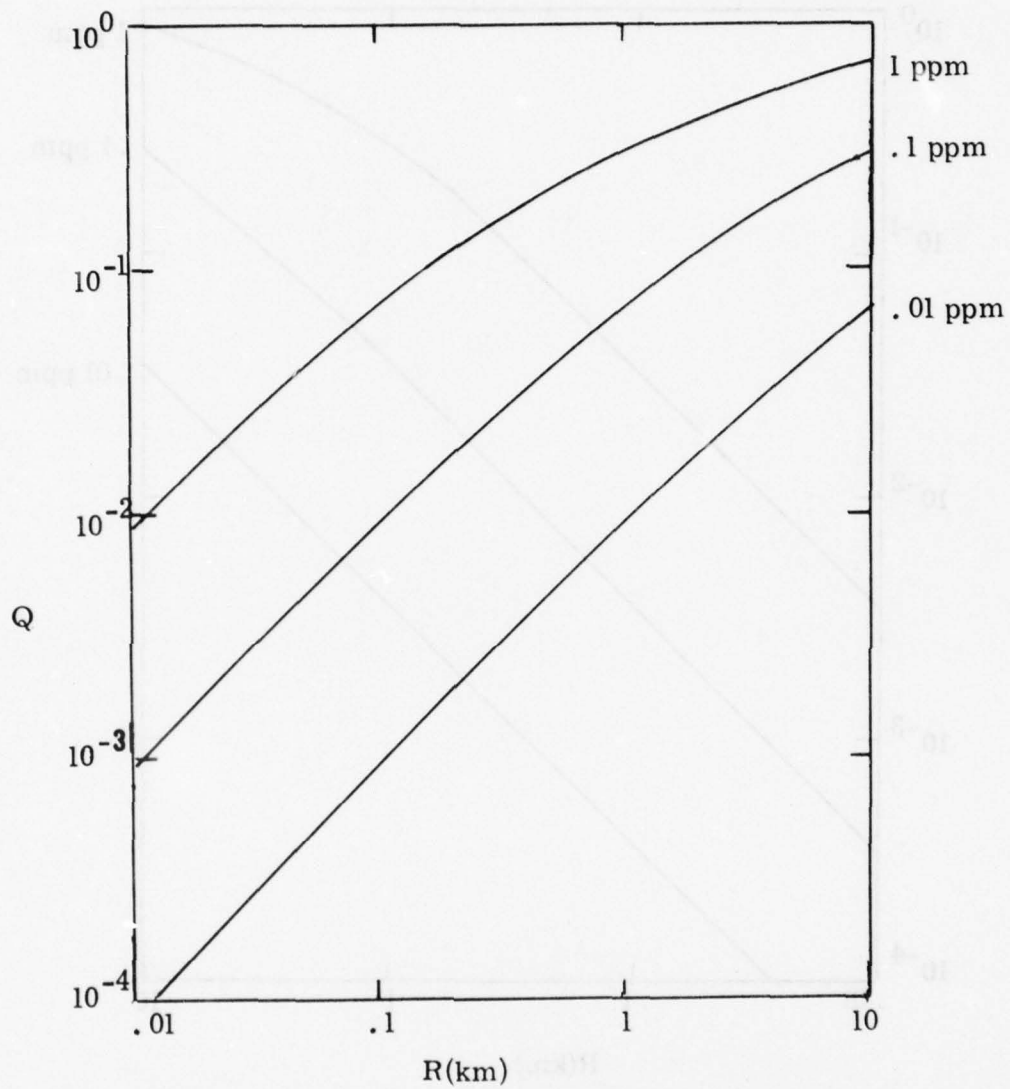


Figure 7.3.5-8e. Q for O_3 versus range for three levels of concentration.

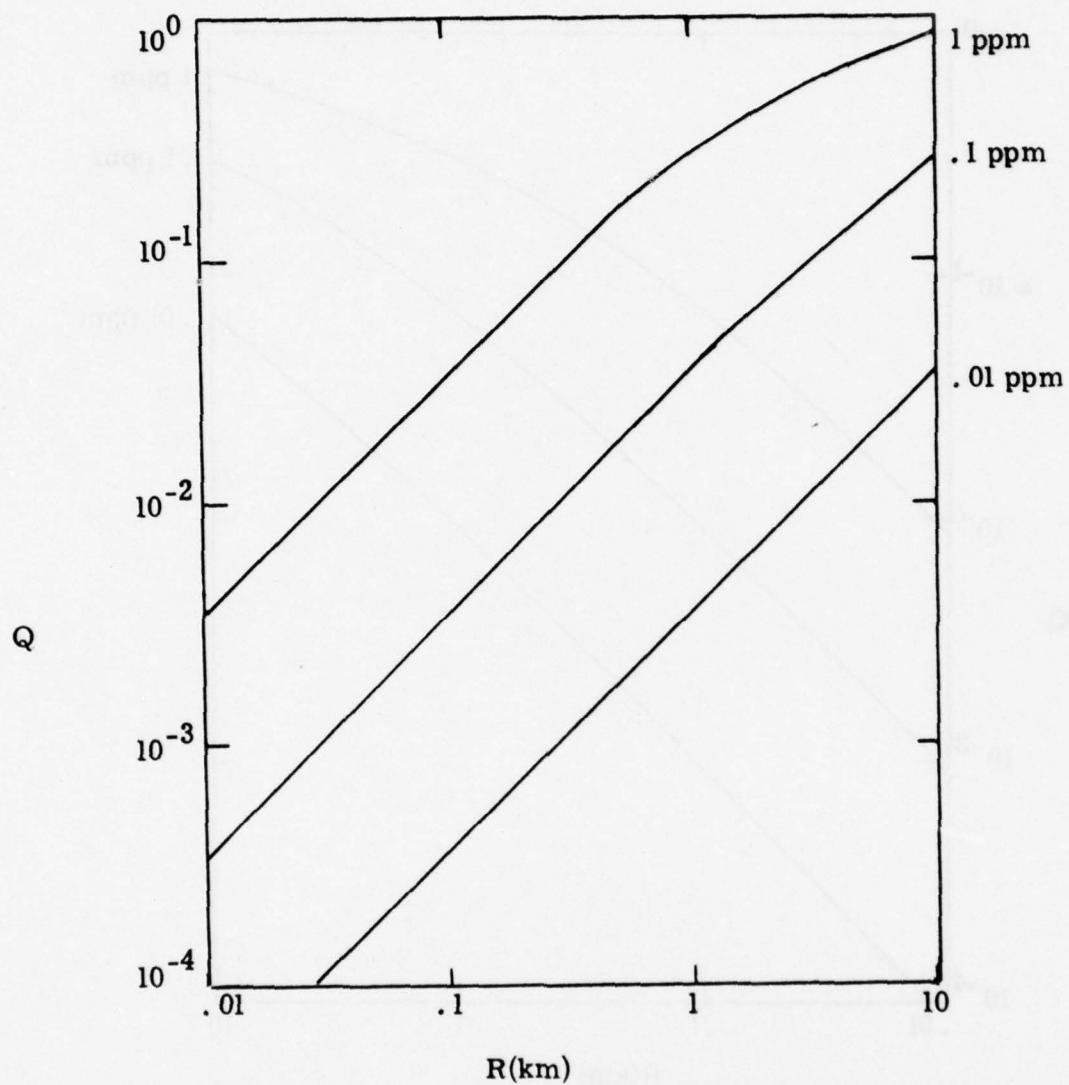


Figure 7.3.5-8f. Q for HCHO versus range for three levels of concentration.

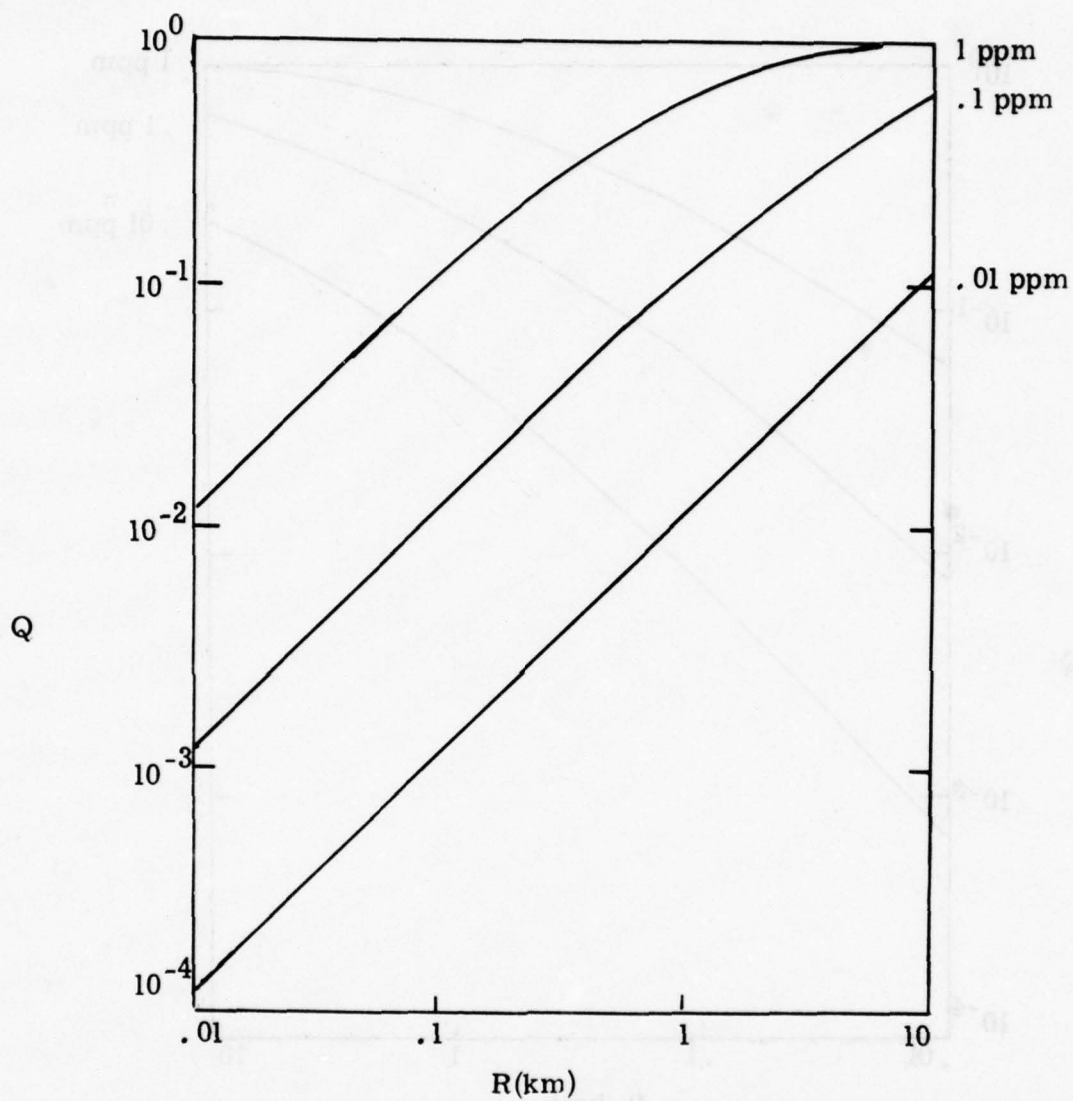


Figure 7. 3. 5-8g. Q for PAN versus range for three levels of concentration.

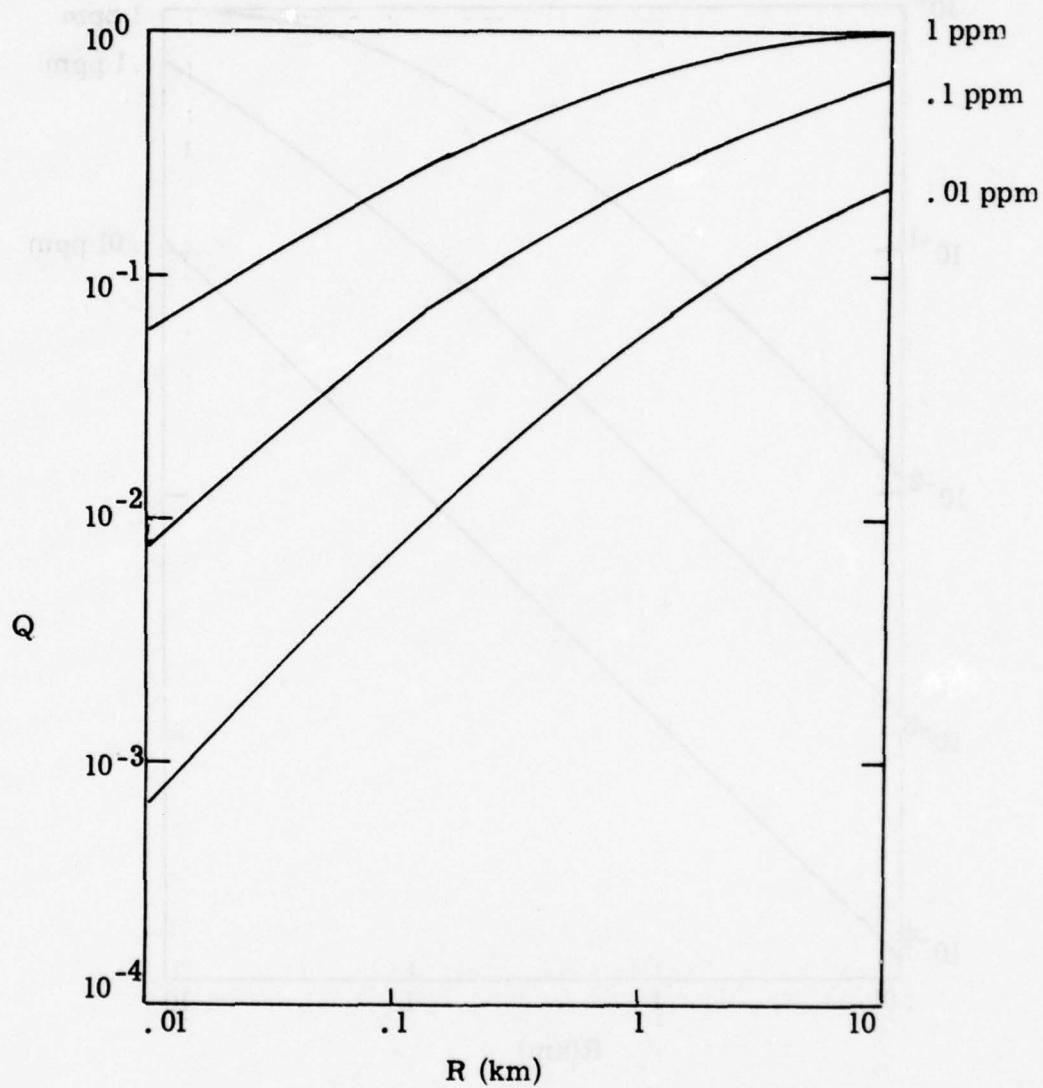


Figure 7. 3. 5-8h. Q for C_2H_4 versus range for three levels of concentration.

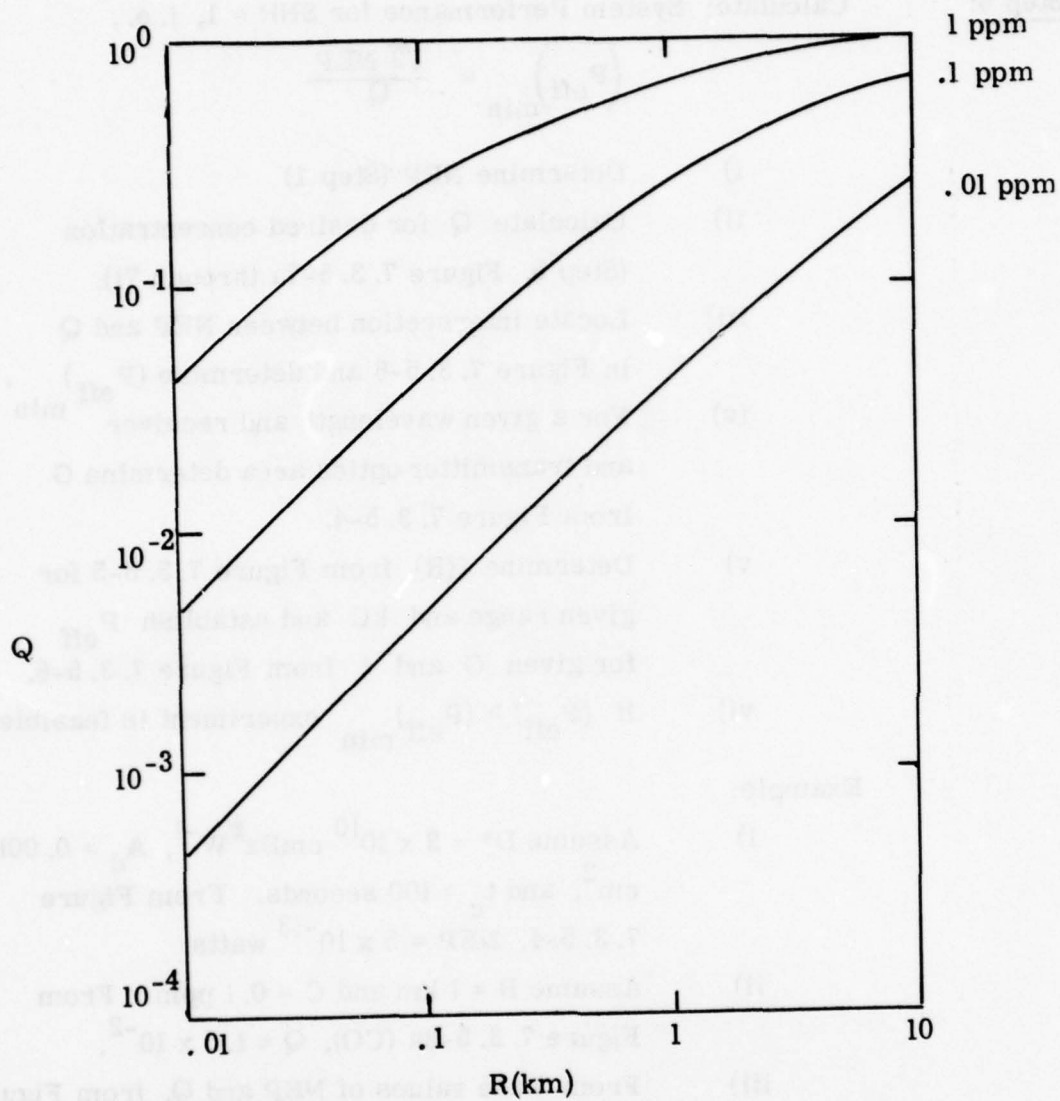


Figure 7. 3. 5-8i. Q for C_6H_6 versus range for three levels of concentration.

Step 6:

Calculate: System Performance for SNR = 1, i. e.,

$$(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{ NEP}}{Q}$$

- i) Determine NEP (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7. 3. 5-7a through 7i).
- iii) Locate intersection between NEP and Q in Figure 7. 3. 5-8 and determine $(P_{\text{eff}})_{\text{min}}$.
- iv) For a given wavelength and receiver and transmitter optics area determine G from Figure 7. 3. 5-4.
- v) Determine $\xi(R)$ from Figure 7. 3. 5-5 for given range and kC and establish P_{eff} for given G and ξ from Figure 7. 3. 5-6.
- vi) If $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$ experiment is feasible.

Example:

- i) Assume $D^* = 3 \times 10^{10} \text{ cmHz}^{\frac{1}{2}} \text{ W}^{-1}$, $A_d = 0.001 \text{ cm}^2$, and $t_c = 100 \text{ seconds}$. From Figure 7. 3. 5-4, $\text{NEP} = 5 \times 10^{-13} \text{ watts}$.
- ii) Assume $R = 1 \text{ km}$ and $C = 0.1 \text{ ppm}$. From Figure 7. 3. 5-8a (CO), $Q = 1.5 \times 10^{-2}$.
- iii) From these values of NEP and Q, from Figure 7. 3. 5-9 $(P_{\text{eff}})_{\text{min}} = 6 \times 10^{-11}$.
- iv) Assume $\lambda = 4.7 \mu\text{m}$ and $A_o = 10^3 \text{ cm}^2$ ($A_o^2 = 10^6$). From Figure 7. 3. 5-5, $G = 7.5 \times 10^4 \text{ Wcm}^2/\mu\text{m}$.
- v) Having assumed above that $R = 1 \text{ km}$ and $C = 0.1 \text{ ppm}$ $k(\text{CO}) = 1.59$ and $a = 0.02$ (tabulation, Step 5). Therefore, $kC = 0.159$. From Figure 7. 3. 5-6, curve 2, at $R = 1 \text{ km}$, $\xi(R) = 10^{-10} \text{ cm}^{-2}$.

Having determined (above) $G = 7.5 \times 10^4$, if $\Delta\lambda$ is assumed to be $0.01 \mu\text{m}$, $G\Delta\lambda$ is 7.5×10^2 . From Figure 7. 3. 5-7 for $G\Delta\lambda = 7.5 \times 10^2$ and $\xi(R) = 10^{-10}$, P_{eff} is 7×10^{-8} watts.

- vi) Since P_{eff} (7×10^{-8} watts) is greater than $(P_{\text{eff}})_{\text{min}}$ (6×10^{-11} watts), the experiment is feasible.

$(P_{\text{eff}})_{\text{min}}$

7.3.5.4t

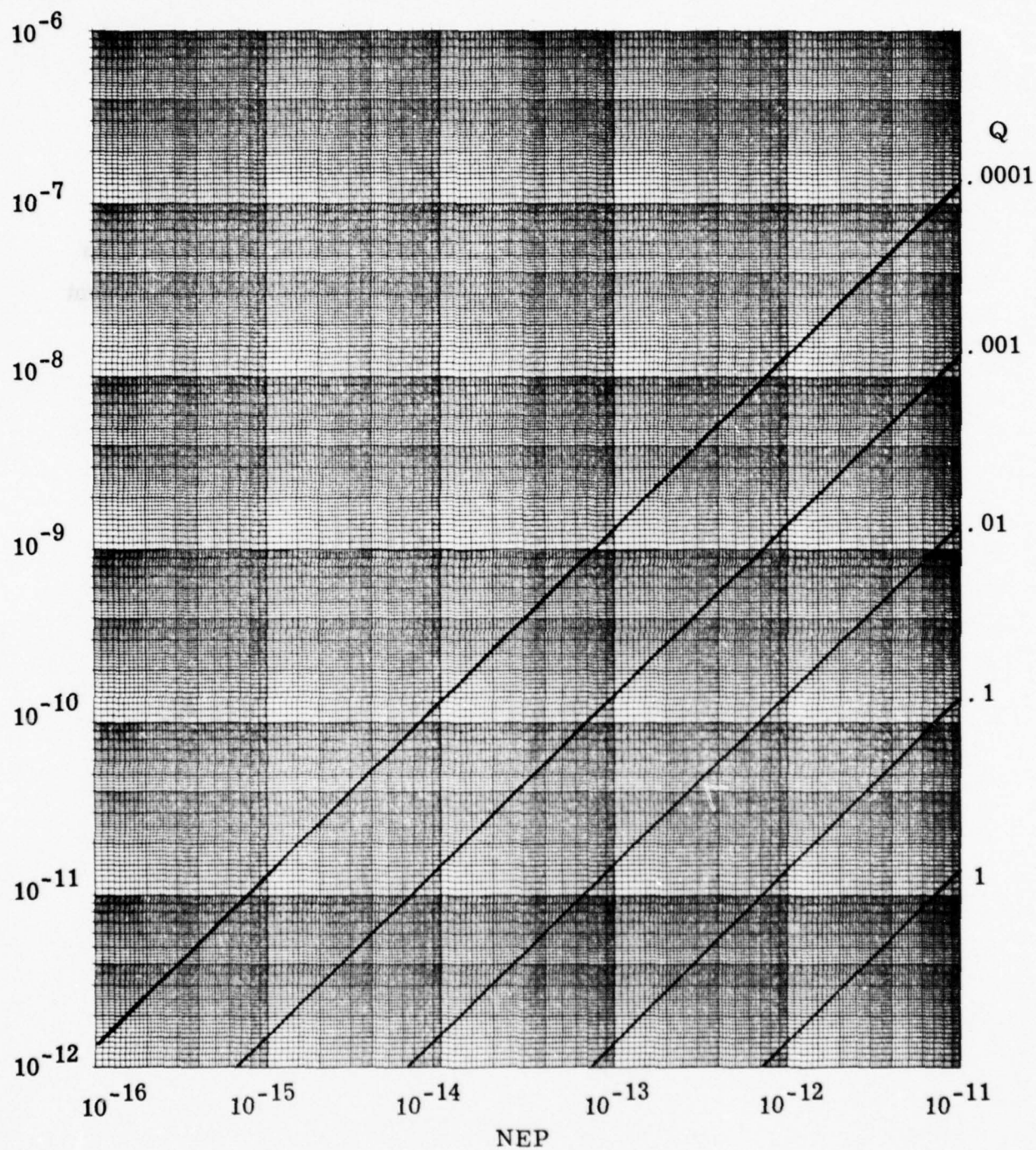


Figure 7.3.5-9. $(P_{\text{eff}})_{\text{min}}$ versus NEP for different values of Q .

7.3.5.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1, and special requirements applicable to all pollutants were described in Sections 7.2.1.5, 7.2.2.5 and 7.2.3.5.

7.3.5.6 Data Analysis Procedure

In general, an analog recording of the scanning spectrophotometer is obtained such as the actual field data shown in Figure 7.3.5-10.

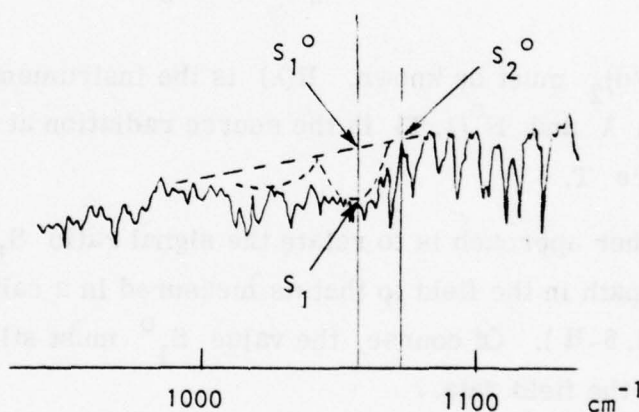


Figure 7.3.5-10. Analog recording over long-path through polluted atmosphere using a blackbody source as transmitter.

The concentration is implicitly determined through the ratio of the two signals S_1 (the attenuated signal S_1^0 (the non-attenuated signal), i. e.,

$$(W/d)_1 = n S_1^0 / S_1$$

where

$$W/d = k C R (1 + kCR/4a)^{-1/2}$$

Since S_1^0 cannot be measured directly, it must be related to a spectral region where there is a known amount of absorption due to the natural species (H_2O , CO_2 , etc.). This relationship is given by

$$S_1^0 = \frac{N^0(\lambda_1, T)}{N^0(\lambda_2, T)} \frac{R(\lambda_1)}{R(\lambda_2)} e^{-(W/d)_2} S_2^0$$

where $(W/d)_2$ must be known, $R(\lambda)$ is the instrument responsivity at wavelength λ and $N^0(\lambda, T)$ is the source radiation at wavelength λ and temperature T .

Another approach is to relate the signal ratio S_1/S_1^0 as measured over long-path in the field to that as measured in a calibration cell (see Figure 7.3.5-11). Of course, the value S_1^0 must still be established reliably in the field data.

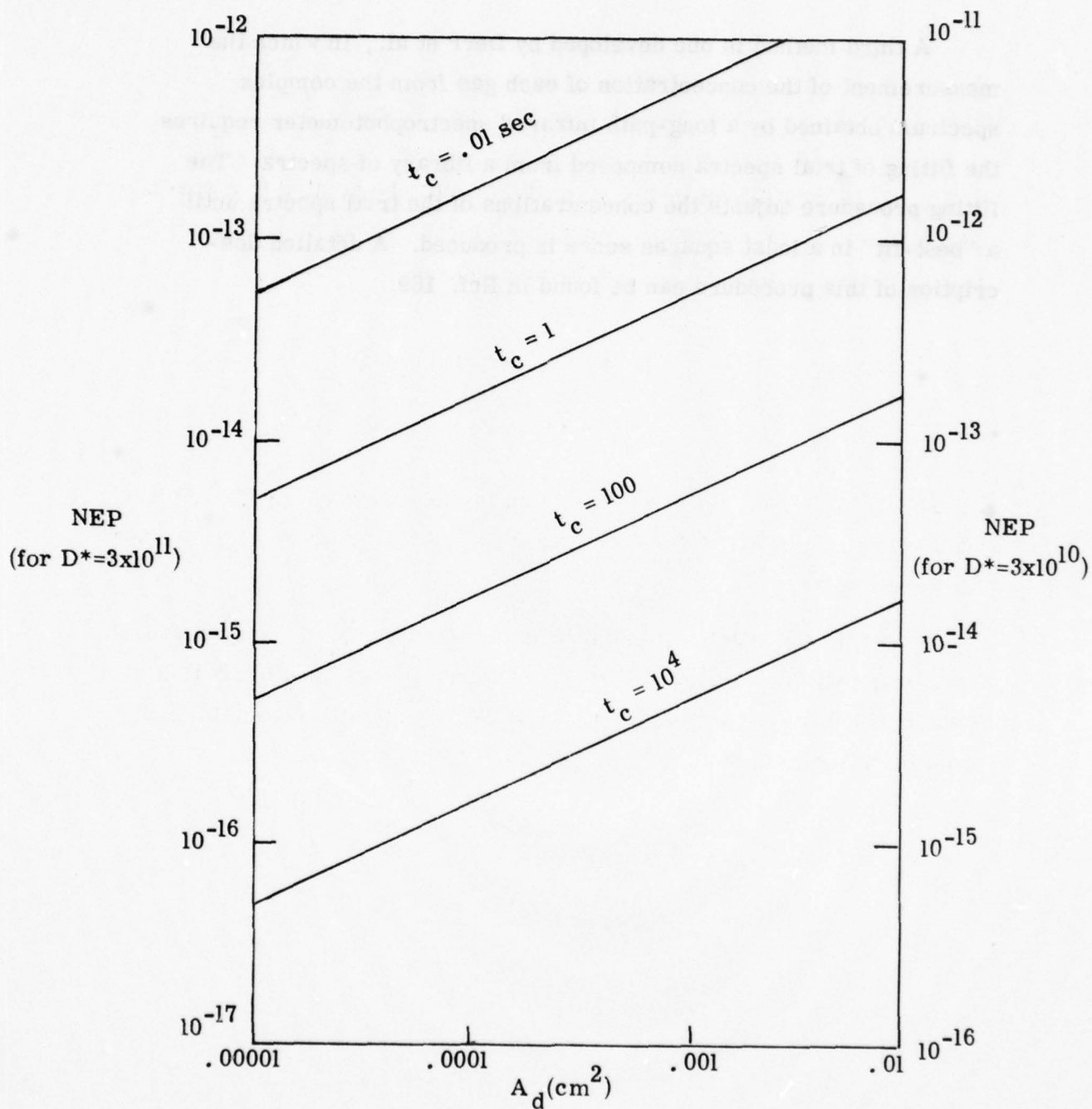


Figure 7.3.5.4 NEP versus A_d for Different Values of Integration Times, Assuming $D^* = 3 \times 10^{10} \text{ cmHz}^{\frac{1}{2}} \text{ W}^{-1}$ (right) and $3 \times 10^{11} \text{ cmHz}^{\frac{1}{2}} \text{ W}^{-1}$ (left).

A third method is one developed by Derr et al., in which the measurement of the concentration of each gas from the complex spectrum obtained by a long-path infrared spectrophotometer requires the fitting of trial spectra composed from a library of spectra. The fitting procedure adjusts the concentrations of the trial spectra until a "best-fit" in a least squares sense is produced. A detailed description of this procedure can be found in Ref. 169.

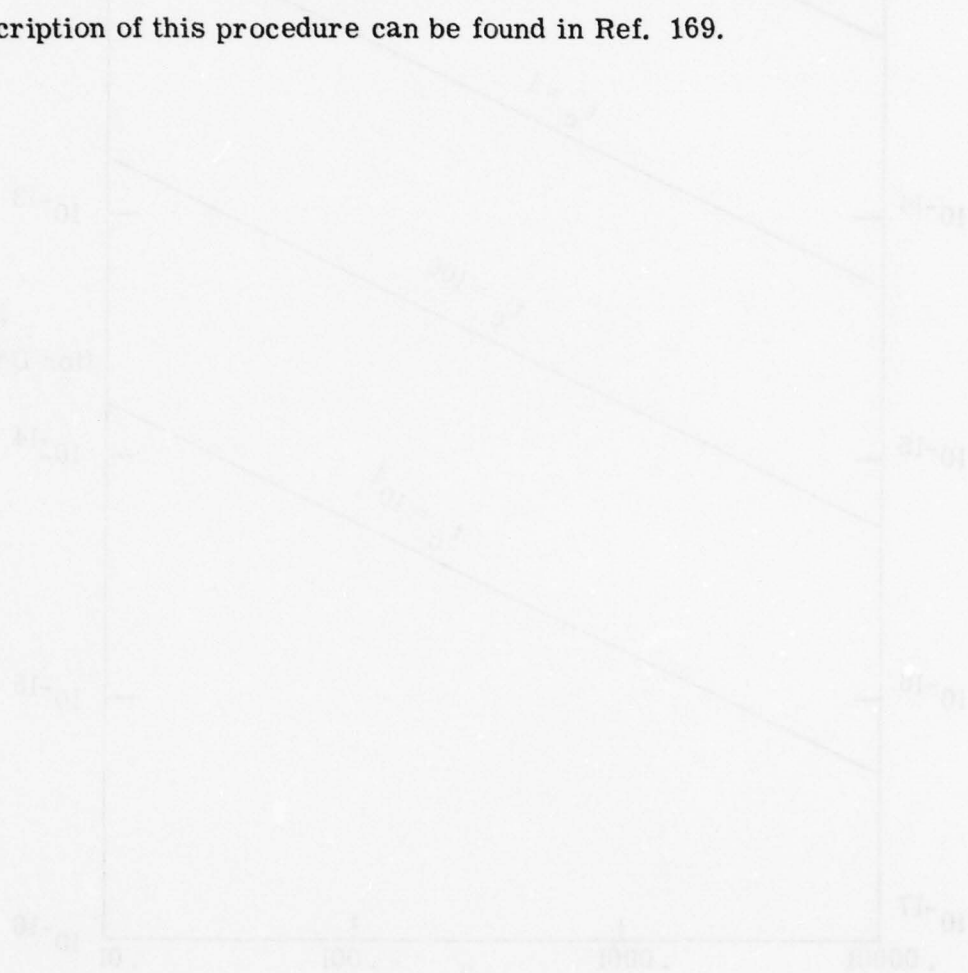


Figure 7.3.5.6d. Infrared spectra of a mixture of gases. The x-axis is Wavenumber (cm⁻¹) and the y-axis is Absorbance. The lines represent the spectra of the individual gases in the mixture.

7.3.6 IR Long-Path with Broadband Source (bi-static)
Using Fourier Transform Spectrometer Receiver

7.3.6.1 Principle of Operation

The infrared long-path transmission technique is used to obtain line averaged concentrations of all gaseous pollutants of interest to NAAQS. A beam from a broadband source is emitted and the transmitted signals are recorded by the Fourier Transform Spectrometer (FTS) receiver as a function of wavelength. By differencing the signals on and off the pollutant lines, the average absorption of the pollutants over the line-of-sight can be determined. The concentration of the pollutant is proportional to the logarithm of the transmission. The proportionality factor is the absorption coefficient which must be known.

7.3.6.2 System Description

The system consists of a broad band source, such as a blackbody, transmitting optics, remote collecting optics, the FTS, electronics and data display. Thus the system is essentially the same as that described in Section 7.3.5.2 except that the dispersive receiver is replaced with the non-dispersive FTS, and the chopper is not needed at the source. A typical system is shown schematically in Figure 7.3.6-1. Details of a typical FTS are given in Figure 7.3.6-2.

7.3.6.3 System Parameters

Commercially available broad band source

Blackbody (~ 1200 K) uncooled

(~ 1500 K) forced air cooled

(~ 1800 K) water cooled

Nernst glower, an electrically heated cylinder of zirconium and yttrium oxide. [272, 273].

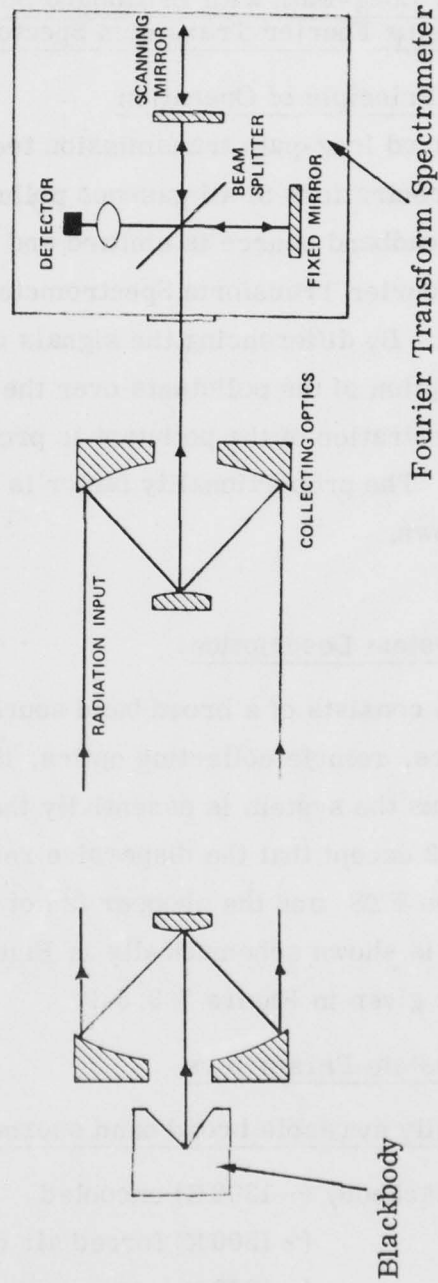


Figure 7. 3. 6-1. Schematic of IR Long-Path System.

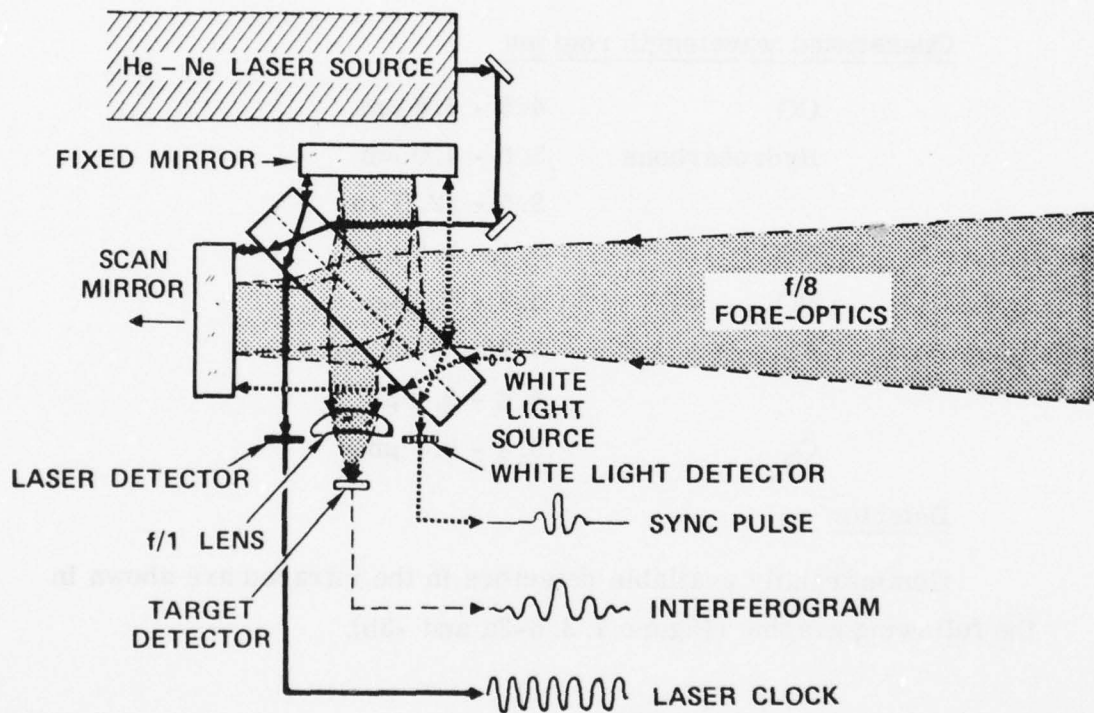


Figure 7.3.6-2. Optical Lay-Out of Fourier Transform Spectrometer.

Commercially available Fourier Transform Spectrometer

Various FTS with and without on-line processors are available from two or three manufacturers. They may cover any part or all of the thermal infrared region depending on the choice of optical components, e. g. windows, beamsplitter, and detector, in the FTS.

Operational wavelength regions

CO	4.5 - 4.8 μm
Hydrocarbons	3.0 - 4.0 μm
	9.5 - 12.0 μm
NO	5.1 - 5.5 μm
NO ₂	3.3 - 3.6 μm
SO ₂	3.95 - 4.05 μm
	8.4 - 9.0 μm
O ₃	9.4 - 9.8 μm

Detector

Commercially available detectors in the infrared are shown in the following graphs (Figure 7. 3. 6-3a and -3b).

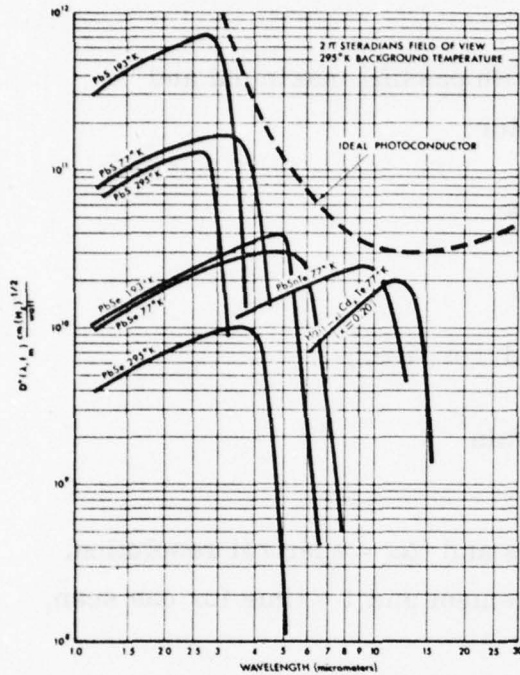


Figure 7. 3. 6-3a

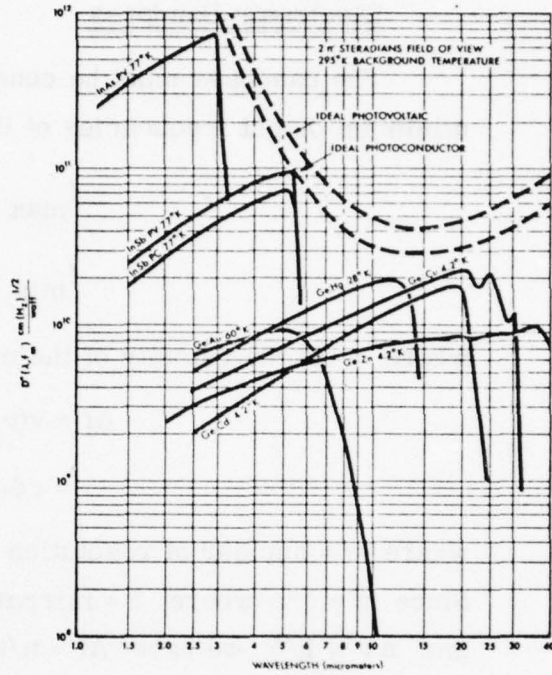


Figure 7. 3. 6-3b

Optics

Collecting Aperture

$$A_o$$

Solid Angle

$$\Omega_o$$

Optical Efficiency

$$\eta_{opt}$$

Detector Optics

$$A_d \Omega_d (= A_o \Omega_o)$$

It should be noted that, for the FTS, Ω_o is related to the spectral resolution $\Delta\nu$, by

$$(\Omega_o)_{max} = 2\pi \frac{\Delta\nu}{\nu_{max}}$$

These optical parameters are variables that must be chosen to fulfill the operational requirements (shown in the following).

Electronic Bandpass

The bandpass must be consistent with passing maximum and minimum output frequencies of the detector:

$$f_{\max} = v \nu_{\max}$$

$$f_{\min} = v \nu_{\min}$$

where v is the velocity of the moving mirror; i.e.,

$$\begin{aligned} \Delta f &= v(\nu_{\max} - \nu_{\min}) \\ &= v\Delta\nu n \end{aligned}$$

where n = number of resolution elements and $\Delta\nu$ = spectral resolution. Since $v = \delta/t$ where δ = mirror displacement and t = time for one scan, and $\Delta\nu = 1/\delta$, we have $\Delta f = n/t$.

7. 3. 6. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The procedure follows exactly that given for the IR long path system with a dispersive receiver described in Section 7. 2. 6. 4.

There are two main advantages⁽²⁶⁸⁾ for the FTS system compared to the dispersive system, assuming that the transmitting and collecting optics are optimally designed for each system. The first is Fellgett's advantage:

The signals from all spectral elements are recorded in parallel rather than sequentially as in the dispersive system. Thus for n resolution elements the FTS records the spectrum n times faster than the dispersive spectrometer, or if each system takes the same time the SNR of the FTS is $n^{1/2}$ times greater.

The second is Jacquinot's advantage:

The FTS has a larger etendue (throughput). The ratio of throughputs for the FTS and the grating spectrometer (GS) is given approximately by

$$\frac{A\Omega(\text{FTS})}{A\Omega(\text{GS})} = 2\pi \frac{F}{L}$$

where F is the focal length of the collimator and L is the slit height. This ratio is typically 100 to 200.

The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q'}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\ln Q' = \ln P/P'$$

$$P = G/R^2 e^{-(w/d)_1} \Delta\lambda$$

$$P' = G/R^2 e^{-(w/d)_2} \Delta\lambda$$

$$G = \eta A_t A_r N^0(\lambda, T)$$

$$w/d = kCR(1 + kCR/4a)^{-1/2}$$

$$dP = \text{NEP} = (A_d/4\tau)^{1/2}/D^*$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2 \text{NEP}}}$$

where

$$Q = (w/d)_2 - (w/d)_1$$

$$P_{\text{eff}} = G \xi(R) \Delta \lambda$$

$$\xi(R) = R^{-2} e^{-(w/d)}$$

In the following a stepwise description for the calculation of SNR is given:

Step 1:

Calculate: NEP

Assume: $D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ (representative for MWIR to LWIR)

$D^* = 3 \times 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ (representative for SWIR)

Result: Plot in Figure 7.3.6-4 shows NEP versus A_d for different Δf . ($\Delta f = 1/4 t_c$)

Step 2:

Calculate: G

Assume: $T = 1600 \text{ K}$

$$\eta = .1$$

Result: Plot in Figure 7.3.6-5 shows G versus λ for different typical values of A_0

Step 3:

Calculate: $\xi(R) = R^{-2} e^{-(w/d)}$

Assume: $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.3.6-6 shows $\xi(R)$ versus R for the above values of kC and six values of a .

Curve (1)	$kC = 0$
(2)	$kC = .3, a = .01$
(3)	$kC = 1, a = .01$
(4)	$kC = 3, a = .01$
(5)	$kC = .3, a = 10$
(6)	$kC = 1, a = 10$
(7)	$kC = 3, a = 10$

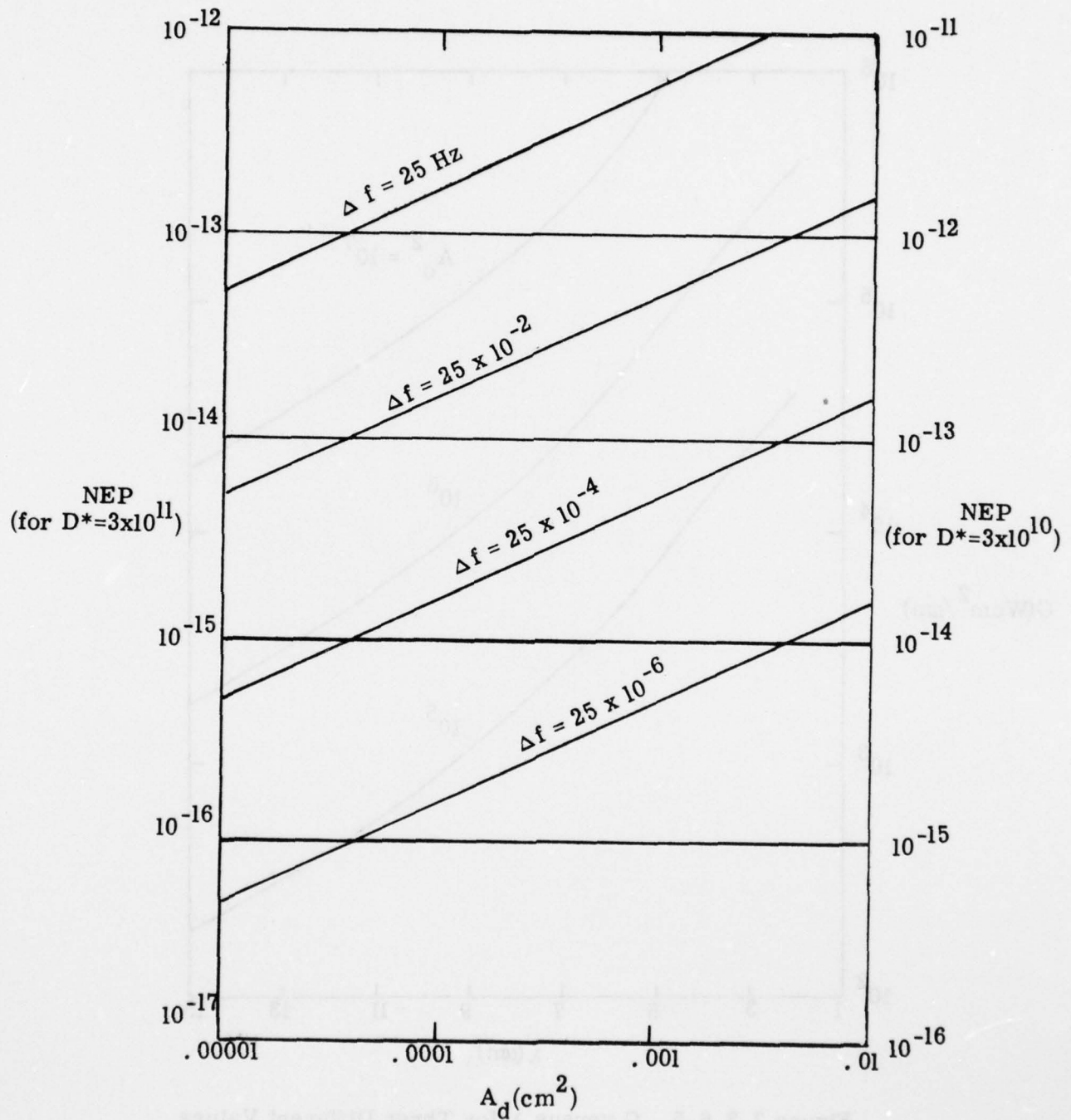


Figure 7.3.6-4. NEP Versus A_d for Different Electronic Bandpasses. Assuming $D^* = 3 \times 10^{10}$ $\text{cm Hz}^2 \text{W}^{-1}$, and 3×10^{11} $\text{cm Hz}^2 \text{W}^{-1}$.

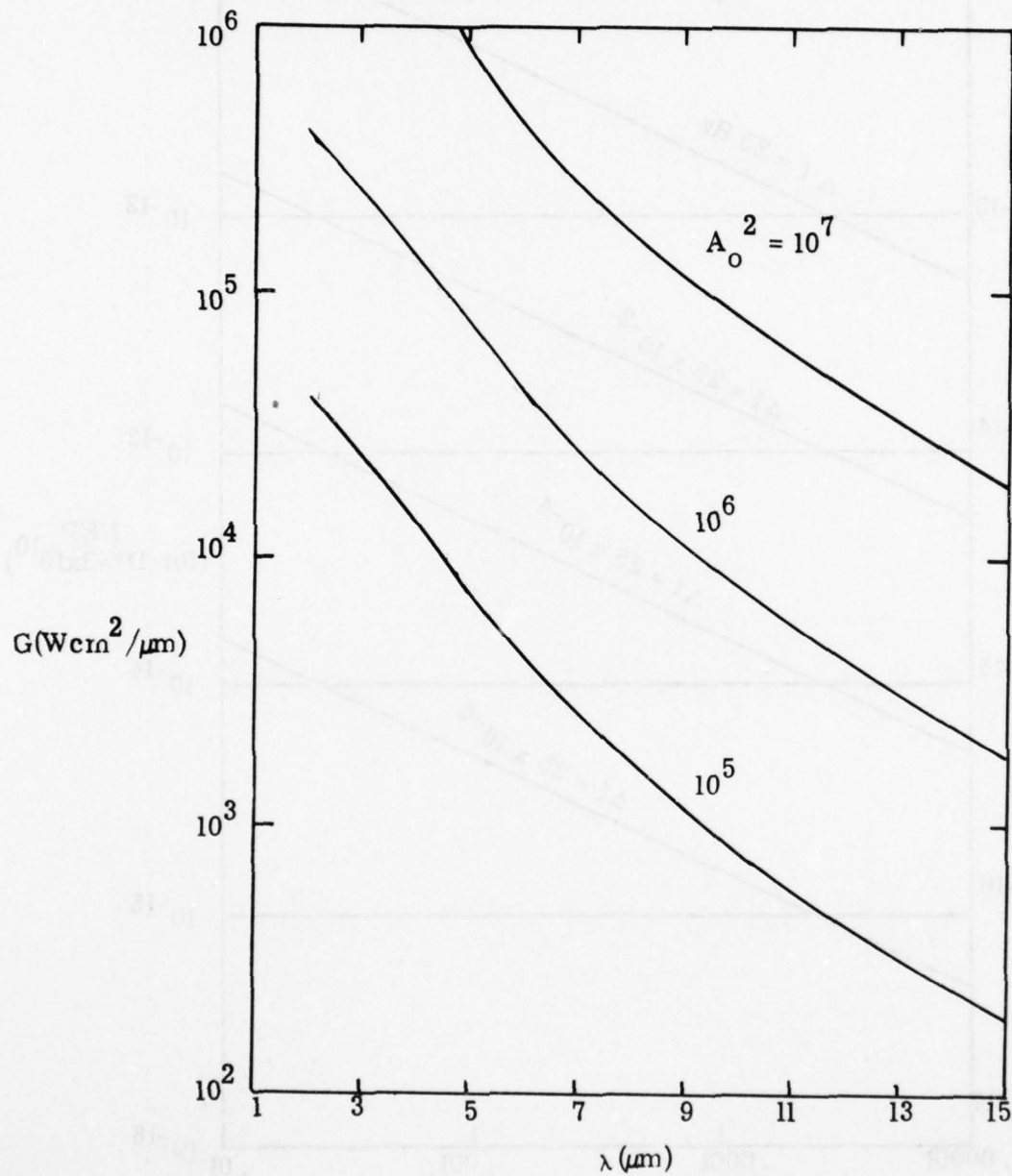
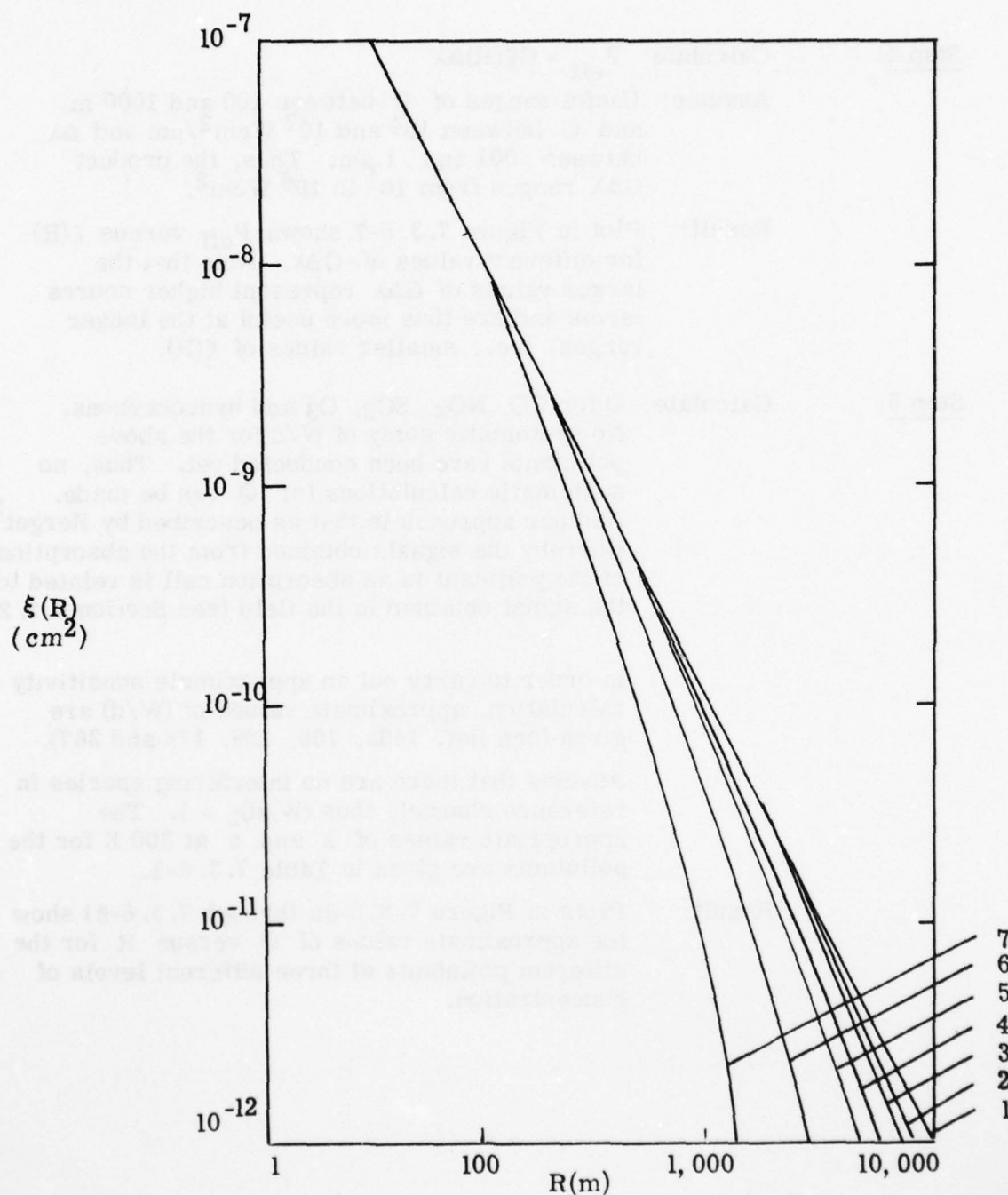


Figure 7.3.6-5. G versus λ for Three Different Values of (A_o^2) .



Figure

Figure 7. 2. 6-6. $\xi(R)$ versus R for Different Values of kC and a : Curve (1) $kC = 0$;

Curve (2) $kC = .3$, $a = .01$

(3) $kC = 1$, $a = .01$

(4) $kC = 3$, $a = .01$

(5) $kC = .3$, $a = 10$

(6) $kC = 1$, $a = 10$

7-181 (7) $kC = 3$, $a = 10$

Step 4: Calculate: $P_{\text{eff}} = G\xi(R)\Delta\lambda$

Assume: Useful ranges of R between 100 and 1000 m, and G between 10^4 and $10^7 \text{ Wcm}^2/\mu\text{m}$ and $\Delta\lambda$ between .001 and .1 μm . Thus, the product $G\Delta\lambda$ ranges from 10^1 to 10^6 Wcm^2 .

Result: Plot in Figure 7.3.6-7 shows P_{eff} versus $\xi(R)$ for different values of $G\Delta\lambda$. Note that the larger values of $G\Delta\lambda$ represent higher source terms and are thus more useful at the longer ranges, i. e., smaller values of $\xi(R)$.

Step 5: Calculate: Q for CO , NO_x , SO_2 , O_3 and hydrocarbons. No systematic study of W/d for the above pollutants have been conducted yet. Thus, no systematic calculations for Q can be made. Another approach is that as described by Herget⁽²⁴⁶⁾, whereby the signals obtained from the absorption of the pollutant in an absorption cell is related to the signal obtained in the field (see Section 5. 3. 2. 2).

In order to carry out an approximate sensitivity calculation, approximate values of (W/d) are given (see Ref. 146a, 166, 169, 176 and 267).

Assume that there are no interfering species in reference channel, thus $(W/d)_2 = 1$. The appropriate values of k and a at 300 K for the pollutants are given in Table 7.3.6-1.

Result: Plots in Figure 7.3.6-8a through 7.3.6-8i show the approximate values of Q versus R for the different pollutants at three different levels of concentration.

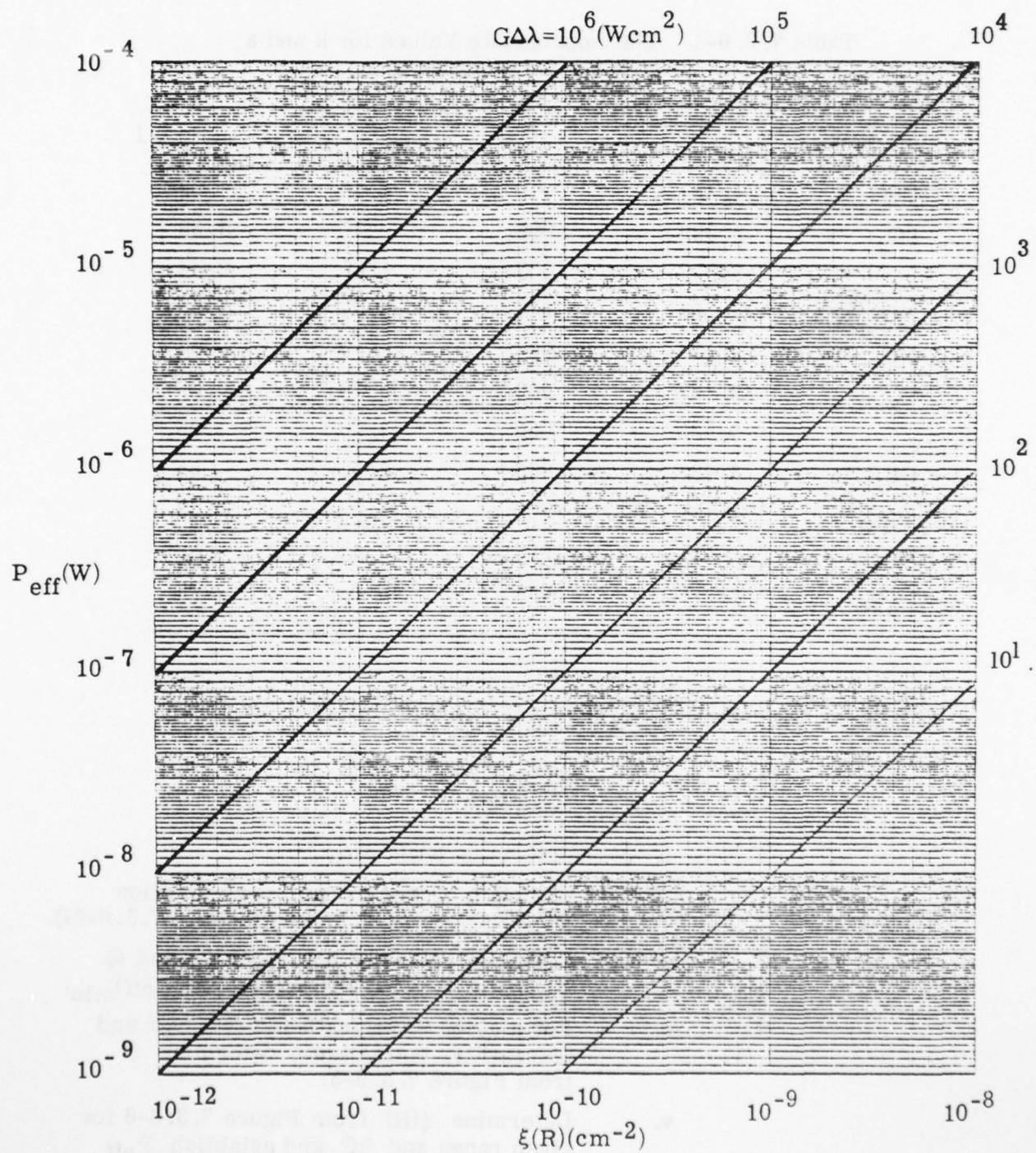


Figure 7. 3. 6-7. P_{eff} versus $\xi(R)$ for Different Values of $G\Delta\lambda$.

Table 7.3.6-1. The Appropriate Values for k and a at 300 K for Pollutants.

Pollutant	λ (μm)	$\Delta\lambda$ (μm)	k (cm atm) ⁻¹	a_o (atm) ⁻¹
CO	4.551	.010	1.59	.02
SO ₂	3.996	.008	.25	1.39
	8.639	.037	1.08	2.44
NO	5.202	.014	1.01	.08
NO ₂	3.422	.006	1.20	.93
O ₃	9.722	.060	9.15	.05
	0.530	.050	7.90	.05
HCHO	3.433	.006	3.52	.55
C ₂ H ₄	10.563	.050	73.0	.03
PAN	12.20	.065	12.4	.5
C ₆ H ₆	3.287	.011	46.4	.08

Step 6: Calculate: System Performance for SNR = 1, i.e.,

$$(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{NEP}}{Q}$$

- i. Determine NEP (Step 1)
- ii. Calculate Q for desired concentration (Step 5, Figures 7.3.6-8a through 7.3.6-8i).
- iii. Locate intersection between NEP and Q in Figure 7.3.6-10 and determine $(P_{\text{eff}})_{\text{min}}$.
- iv. For a given wavelength and receiver and transmitter optics area, determine G from Figure 7.3.6-5.
- v. Determine $\xi(R)$ from Figure 7.3.6-6 for given range and kC and establish P_{eff} for given G and ξ from Figure 7.3.6-7.
- vi. If $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$ experiment is feasible.

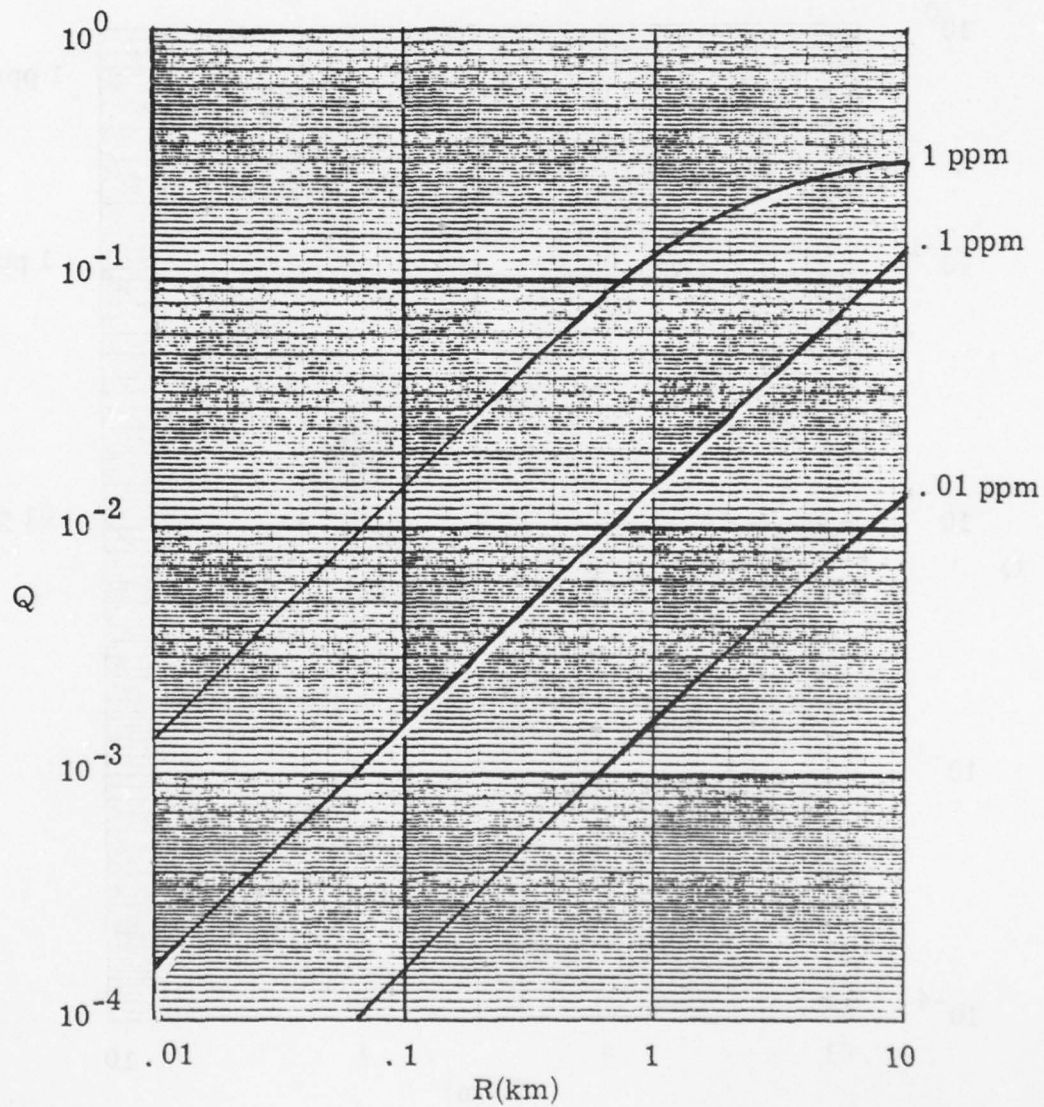


Figure 7. 3. 6-8a. Q for CO versus range for three levels of concentration.

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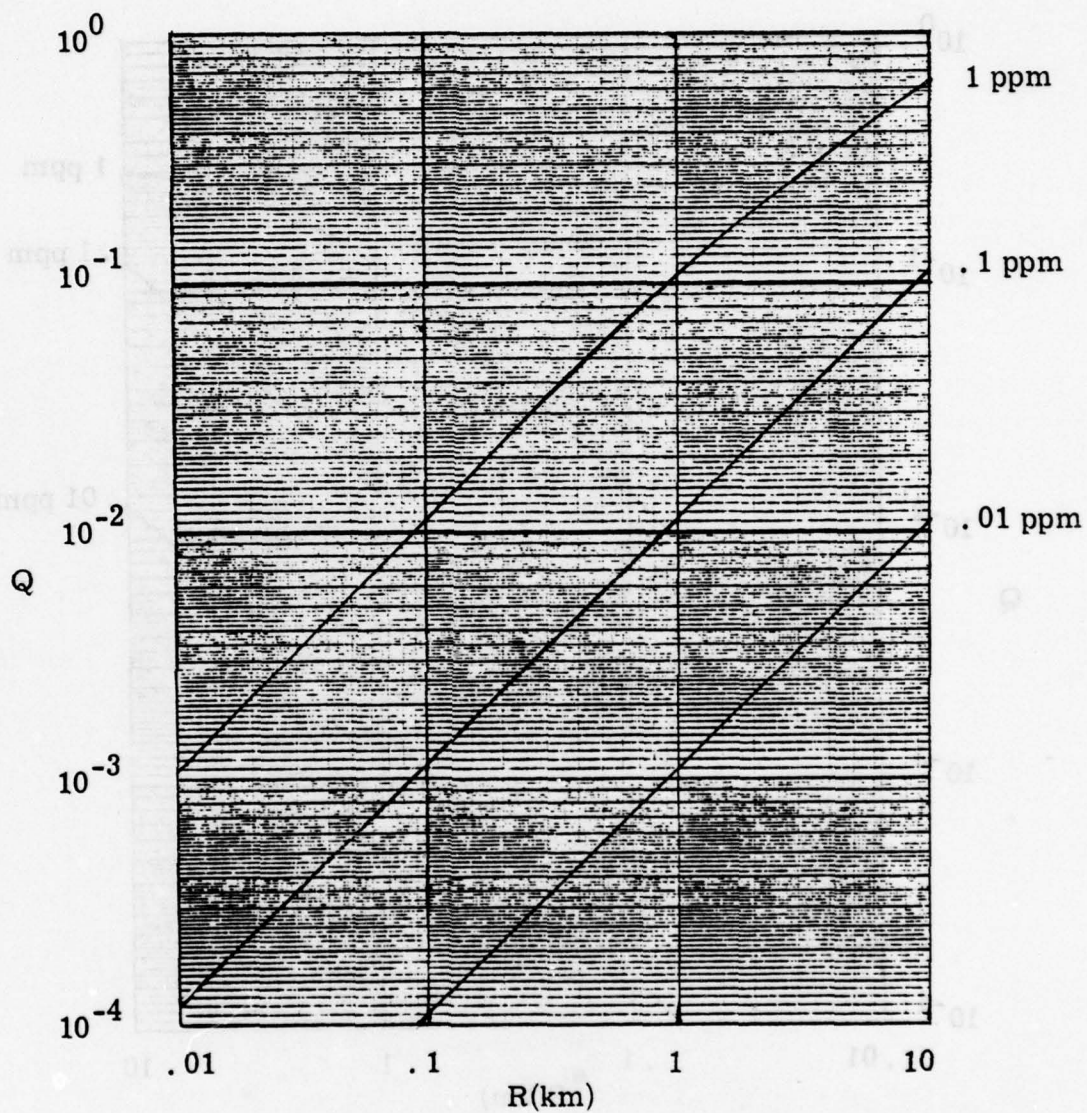


Figure 7. 3. 6-8b. Q for SO_2 versus range for three levels of concentration.

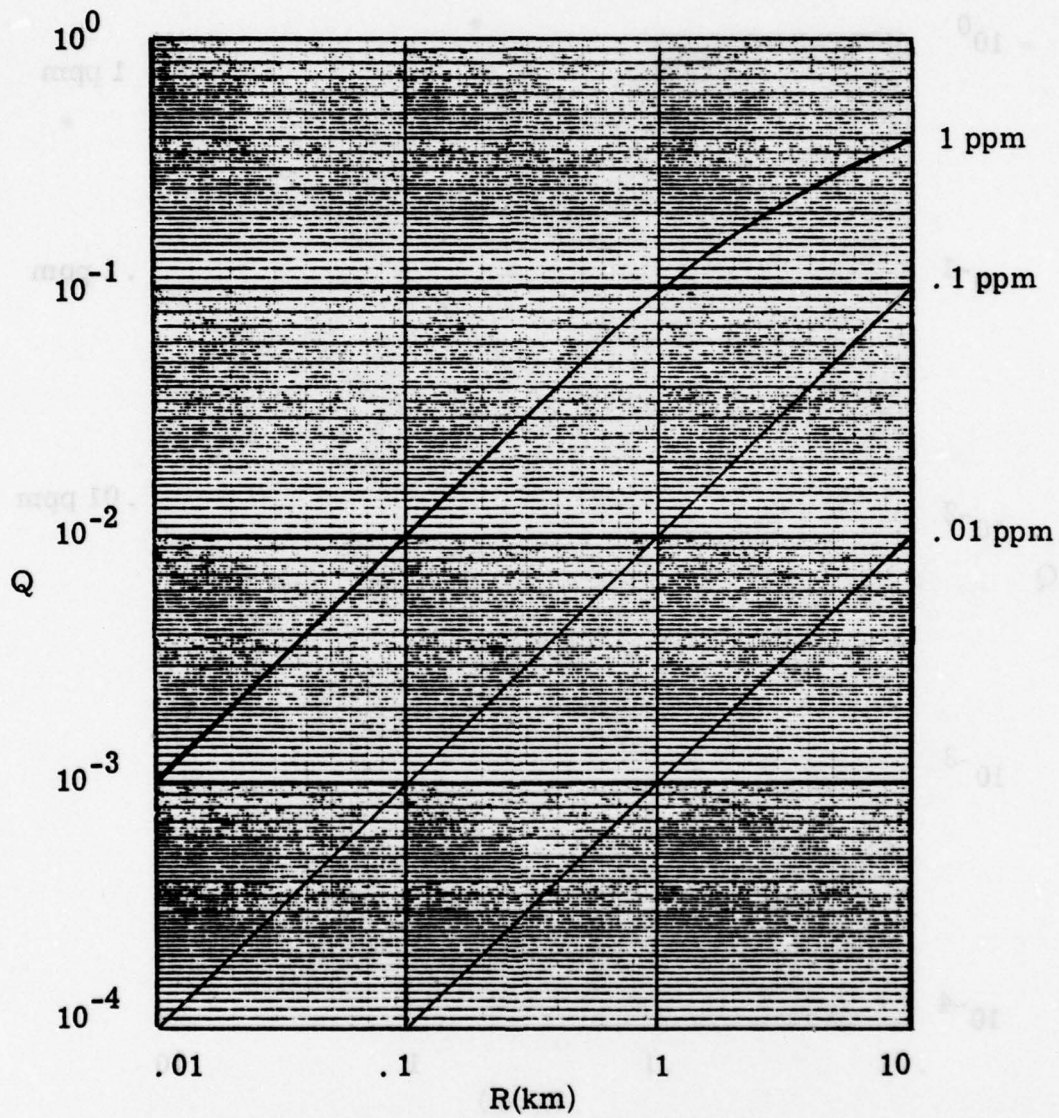


Figure 7. 3. 6-8c. Q for NO versus range for three levels of concentration.

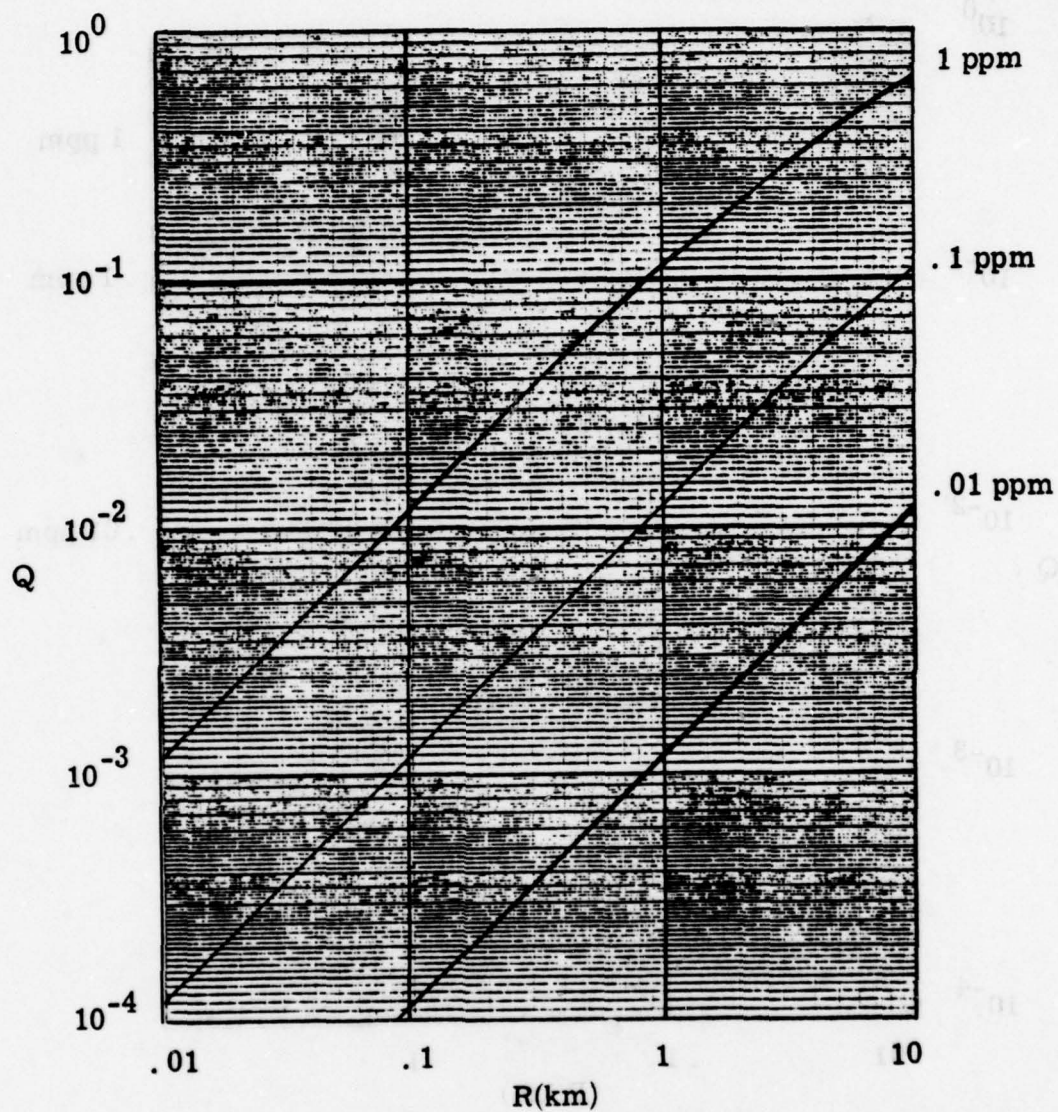


Figure 7. 3. 6-8d. Q for NO_2 versus range for three levels of concentration.

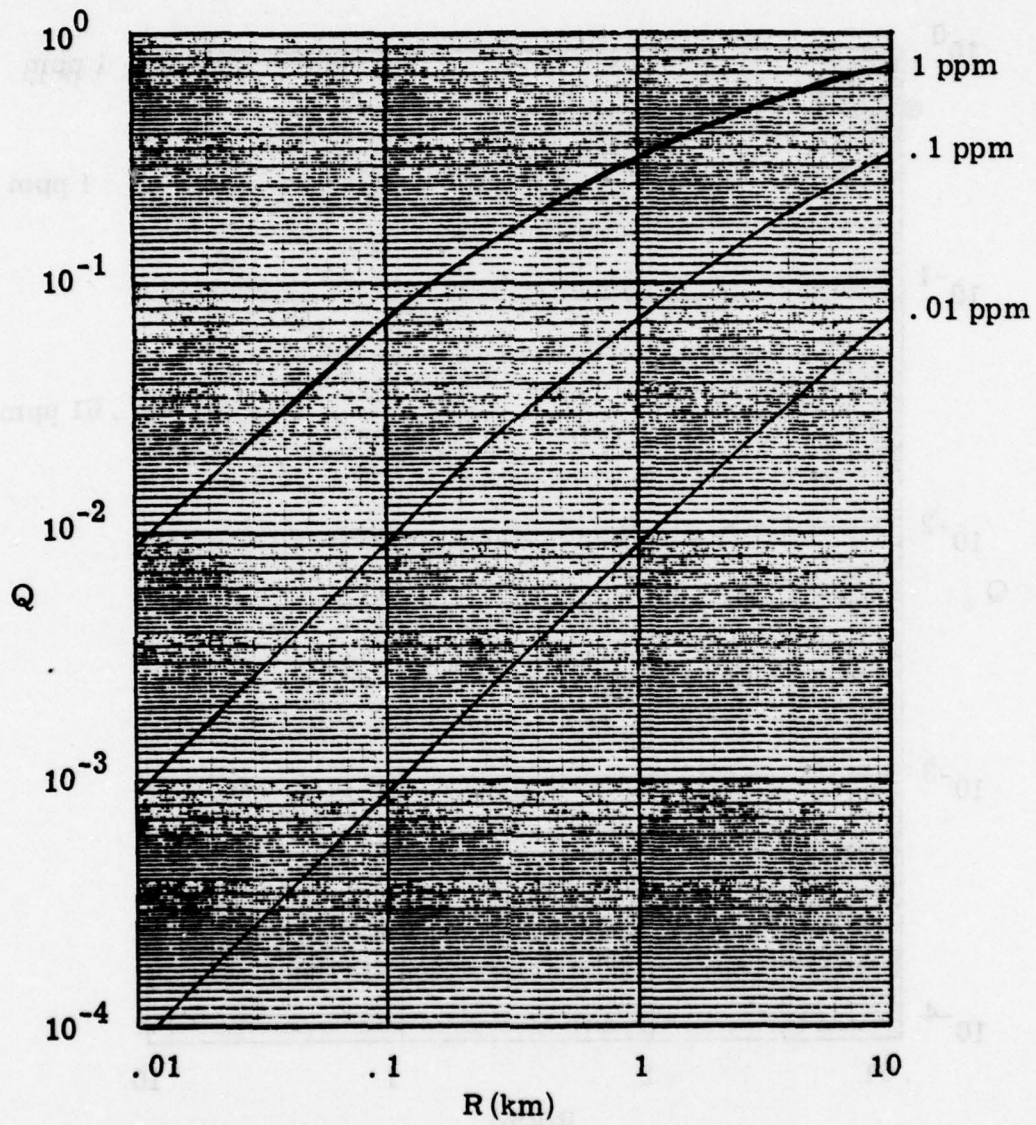


Figure 7. 3. 6-8e. Q for O_3 versus range for three levels of concentration.

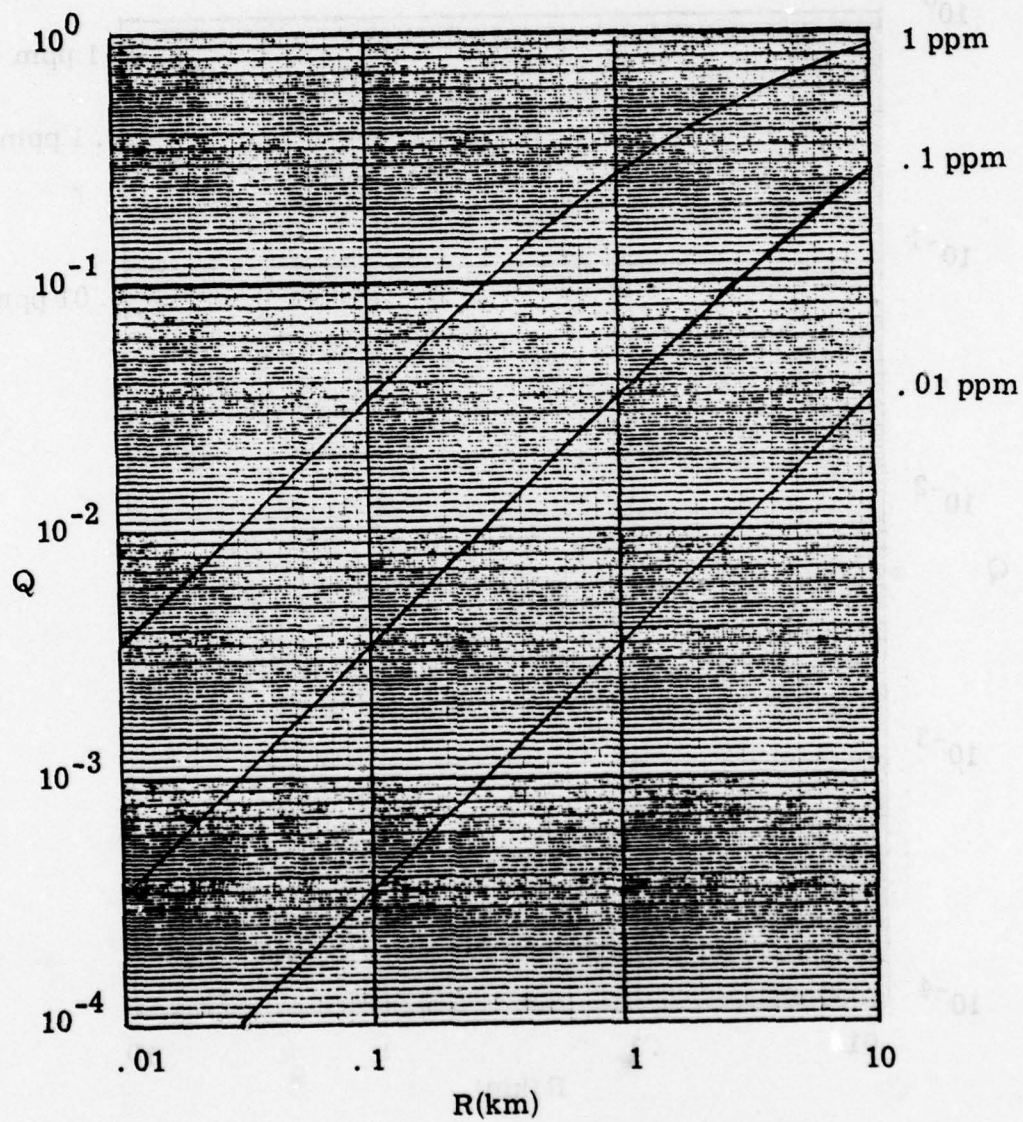


Figure 7. 3. 6-8f. Q for HCHO versus range for three levels of concentration.

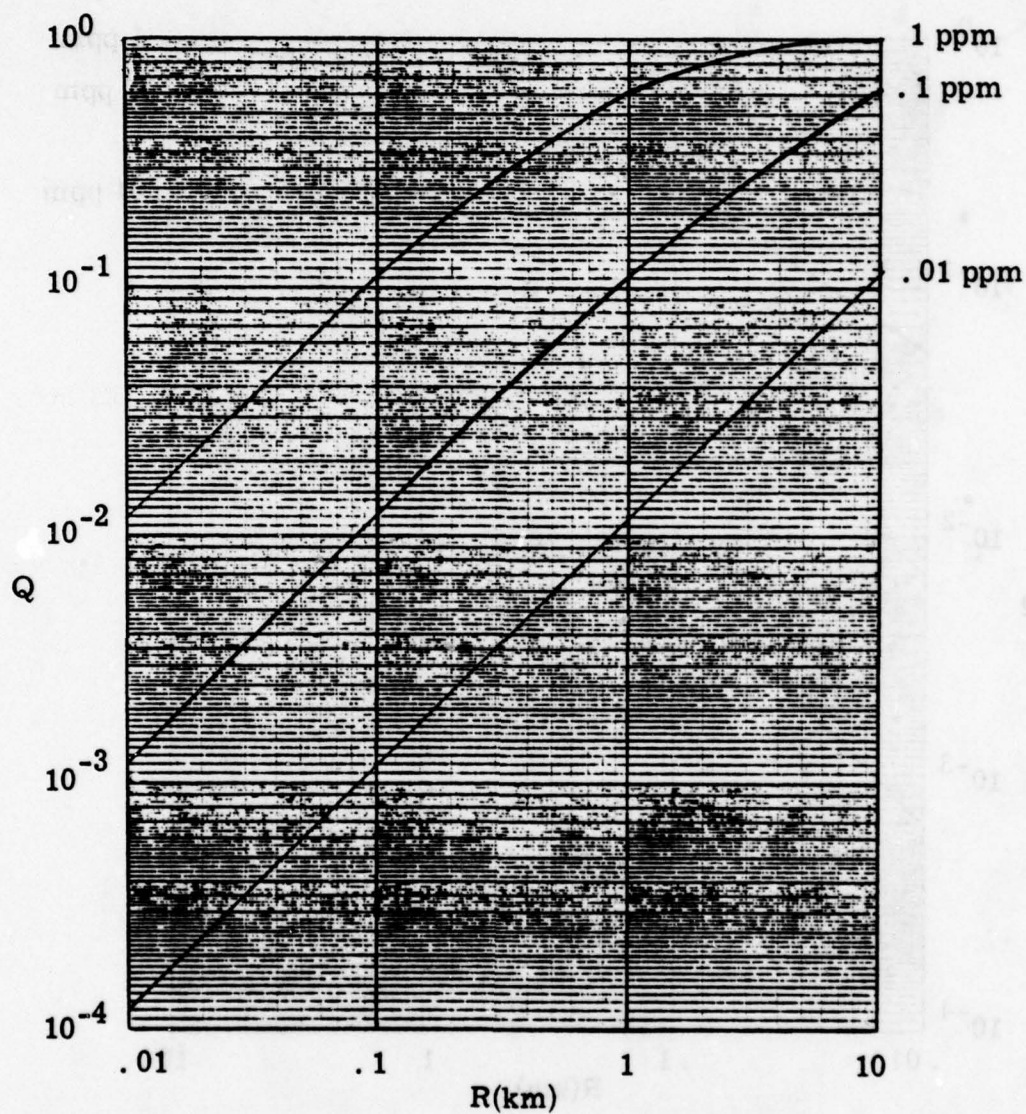


Figure 7. 3. 6-8g. Q for PAN versus range for three levels of concentration.

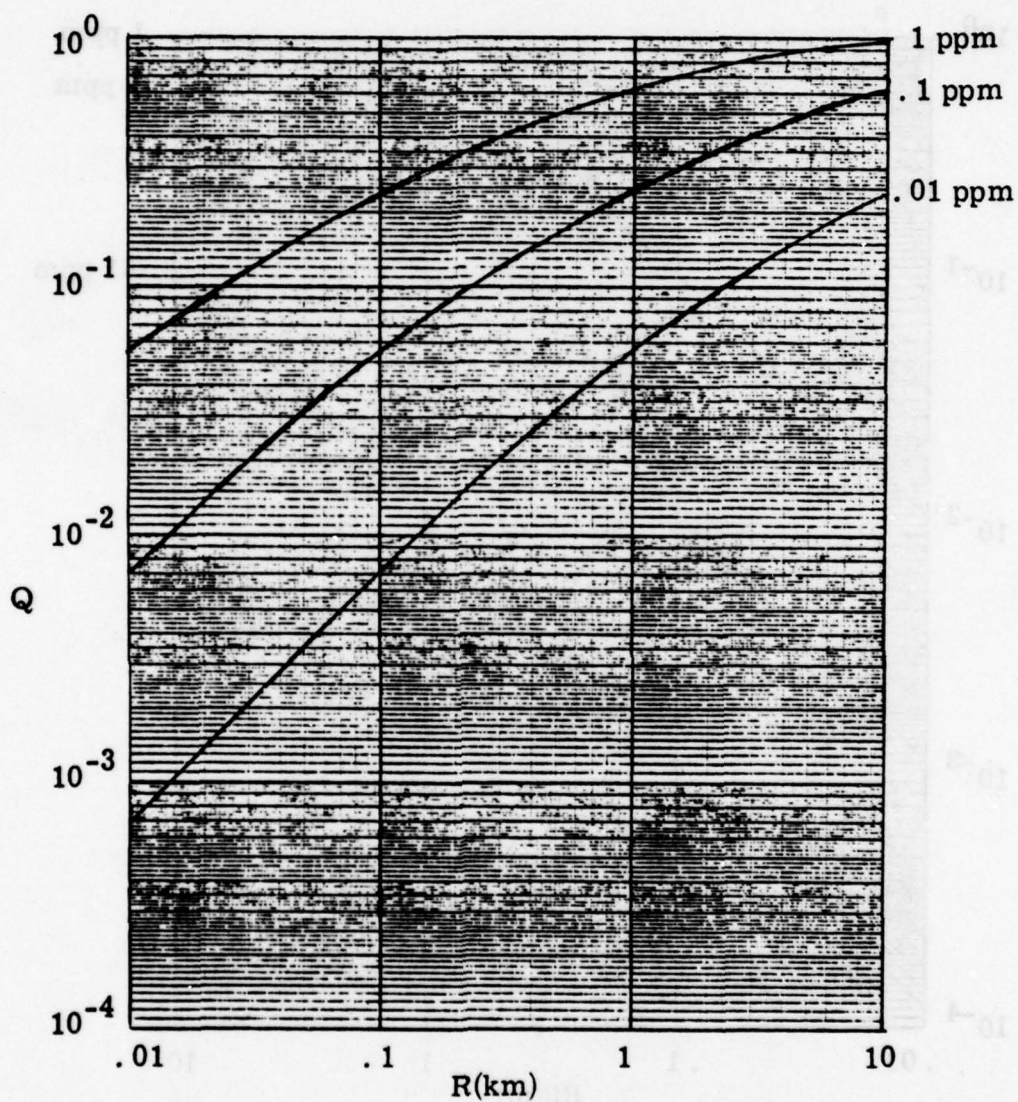


Figure 7. 3. 6-8h. Q for C_2H_4 versus range for three levels of concentration.

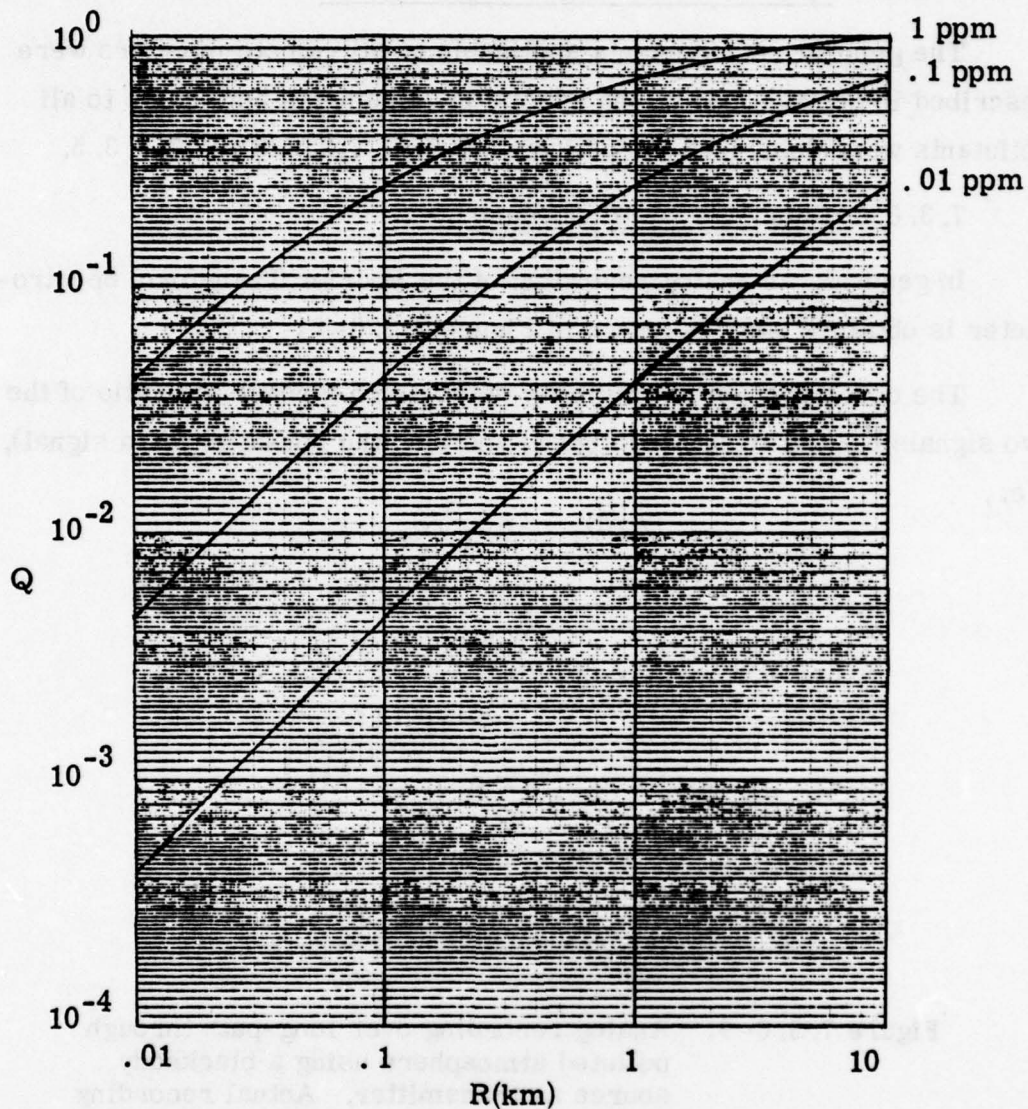


Figure 7. 3. 6-8i. Q for C_6H_6 versus range for three levels of concentration.

7.3.6.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1, and special requirements applicable to all pollutants were described in Sections 7.2.1.5, 7.2.2.5 and 7.2.3.5.

7.3.6.6 Data Analysis Procedure

In general, an analog recording of the Fourier Transform Spectrometer is obtained such as shown in Figure 7.3.6-9.

The concentration is implicitly determined through the ratio of the two signals S_1 (the attenuated signal) and S_1^0 (the non-attenuated signal), i. e.,

$$(W/d)_1 = \ln S_1^0 / S_1$$

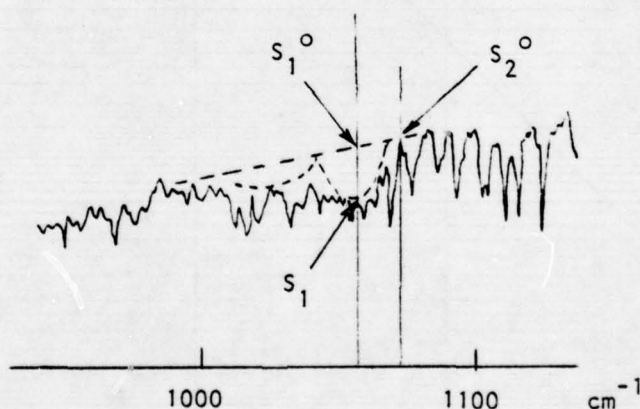


Figure 7.3.6-9. Analog recording over long-path through polluted atmosphere using a blackbody source as transmitter. Actual recording of field data.

where

$$W/d = kCR(1 + kCR/4a)^{-1/2}.$$

Since S_1^0 cannot be measured directly, it must be related to a spectral region where there is a known amount of absorption due to the natural species (H_2O , CO_2 , etc.). This relationship is given by

$(P_{\text{eff}})_{\text{min}}$

7. 3. 6. 6b

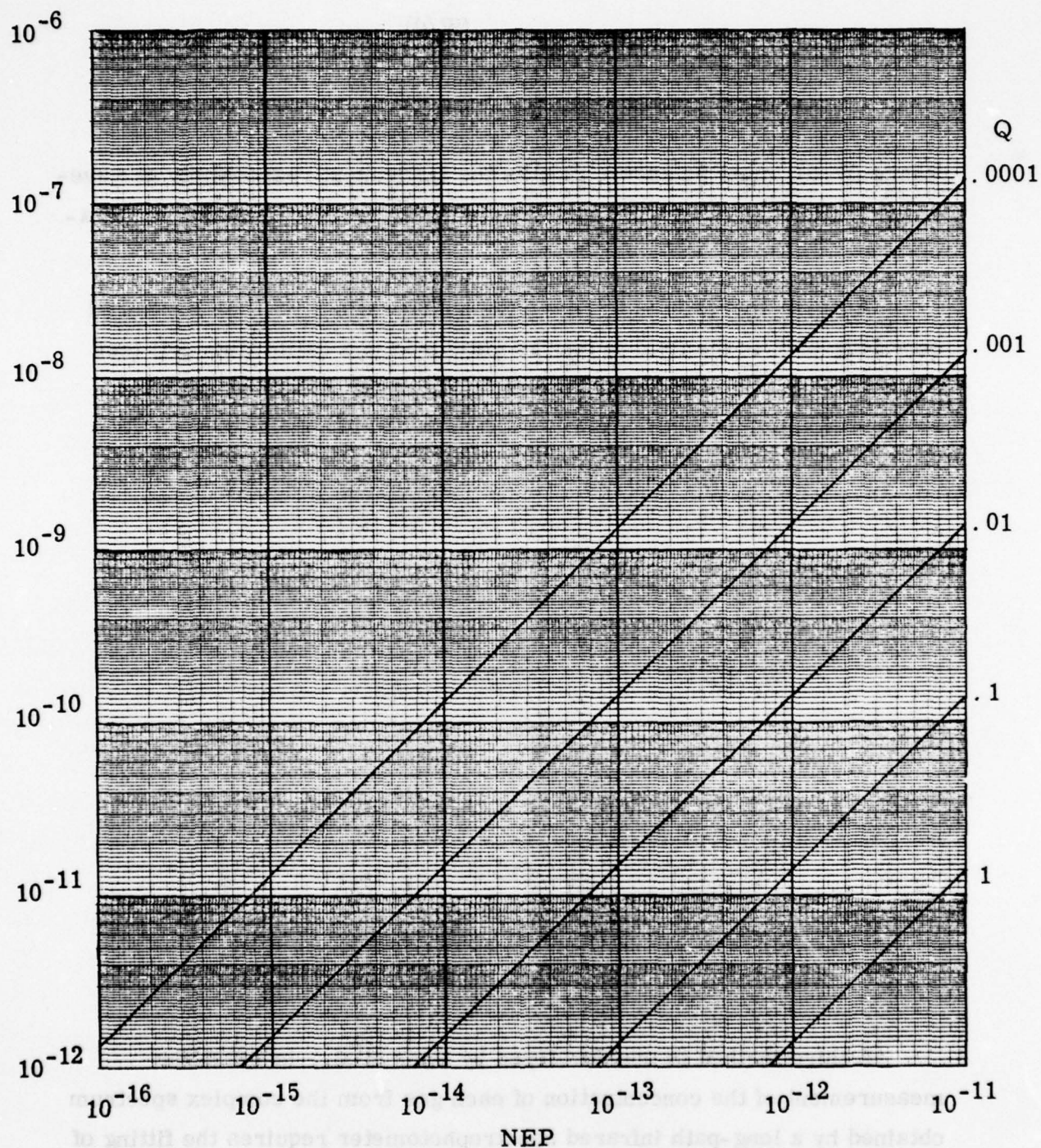


Figure 7. 3. 6-10. $(P_{\text{eff}})_{\text{min}}$ versus NEP for different values of Q .

$$S_1^o = \frac{N^o(\lambda_1, T) R(\lambda_1)}{N^o(\lambda_2, T) R(\lambda_2)} e^{(W/d)_2 S_2^o}$$

where $(W/d)_2$ must be known, $R(\lambda)$ is the instrument responsivity at wavelength λ and $N^o(\lambda, T)$ is the source radiation at wavelength λ and temperature T .

Another approach is to relate the signal ratio S_1/S_1^o as measured over long-path in the field to that as measured in a calibration cell (see Figure 7. 3. 6-11). Of course, the value S_1^o must still be established reliably in the field data.

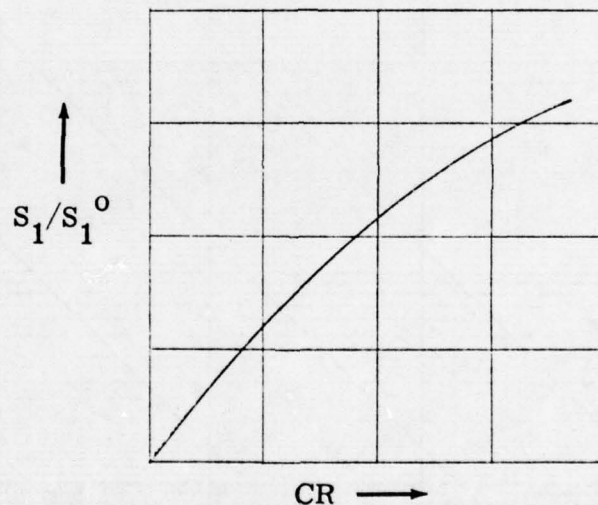


Figure 7. 3. 6-11. Conceptual calibration curve S_1/S_1^o versus the product concentration \bar{x} range.

A third method is one developed by Derr et al., in which the measurement of the concentration of each gas from the complex spectrum obtained by a long-path infrared spectrophotometer requires the fitting of trial spectra composed from a library of spectra. The fitting procedure adjusts the concentrations of the trial spectra until a "best-fit" in a least squares sense is produced. A detailed description of this procedure can be found in Reference 169.

7.3.7 IR Long-Path with Broadband Source Using Gas Filter Correlation Receiver

7.3.7.1 Principle of Operation

Gas filter correlation is a method of determining the concentration of pollutant gas species by measuring the correlation between the unknown atmospheric spectrum and the spectrum of a known sample of the specific pollutant gas which is contained in the instrument. The spectra of other gases have near zero correlation with the spectrum of this particular species and so are intrinsically discriminated against.

The radiant source is broadband and the receiver is non-dispersive. The radiant energy received from the source is passed alternately through the sample of the particular species and through a neutral absorber having the same total transmission as the gas sample. Radiation is absorbed in the gas cell only at those specific spectral line wavelengths which are characteristic of that gas species; in the neutral absorber radiation is absorbed equally at all wavelengths.

The difference in the source energy removed by the gas and the neutral absorber is the desired pollutant concentration signal. If the correlation coefficient between the spectra of the standard and the unknown is zero (random spectral line overlap) the same total energy will be removed from the beam by the neutral and the gaseous absorbers and no net signal results. If the correlation coefficient between the spectra is plus unity (exact spectral line overlap) a signal will result: Less change will be observed in the source energy when transmitted through the gas cell, as compared to the neutral absorber, because the exact wavelengths at which energy is selectively attenuated by the gas cell have already been attenuated by the pollutant, but the neutral absorber will attenuate the source energy non-selectively. The result is a difference signal proportional only to the specific pollutant's absorption. This signal is related by calibration to the average concentration of the specific pollutant over the path between the source and receiver.

7. 3. 7. 2 System Description

The system consists of a broadband radiant source covering the wavelength interval of the pollutant spectral band and a receiver to examine the source radiation after its absorption by the intervening atmosphere.

The system may be bistatic, with a separated source and receiver, or monostatic wherein the source and receiver are adjacent and with a retroreflector defining the far end of the monitored region. In this latter case, the sensitivity is increased because the beam traverses the monitored region twice.

The source is generally a blackbody and is chopped so that its radiation can be distinguished at the detector from spurious background radiation.

The mechanism for alternating the beam between the gas cell and the neutral absorber may be either at the source or at the detector.

A diagram of a typical instrument is shown in Figure 7. 3. 7-1.

7. 3. 7. 3 System Parameters

Source

Numerous commercial radiant sources are available which approximate the blackbody function over the infrared wavelength interval of interest. Temperatures available range to 1800K; 1100K is typical. Higher temperatures may not provide the expected signal improvement as they may necessitate a decrease in the instrument $A \Omega$ parameter. $A \Omega$ is the product of the aperture area A and the solid angle (field of view) Ω . It determines the power collected from a field of radiance and

is therefore a general indicator of sensitivity. A Ω is sometimes called "light grasp" or "etendue".

Throughout a given optical system the beam cross-section area and the beam convergence angle may change individually, but geometric optical laws dictate that their product remains constant. For this reason the A Ω parameter is also given the names "throughput" and "optical invariant".

Spectral radiance for blackbody sources is given in Figure 7.3.7-3 as a function of temperature and wavelength.

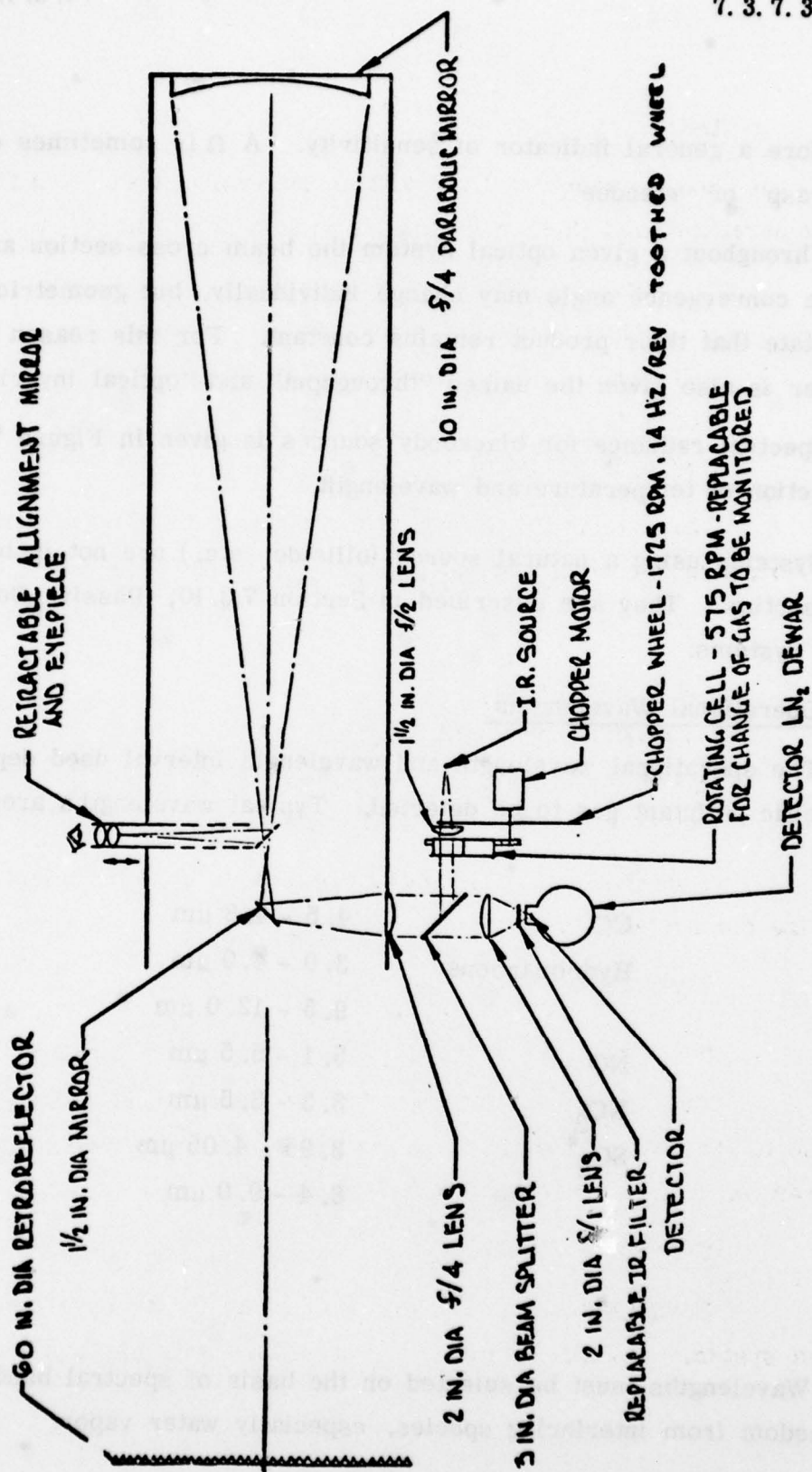
Systems using a natural source (hillside, etc.) are not included in this section. They are described in Section 7.3.10, Passive Downward Looking Systems.

Operational Wavelengths

The operational wavelength and wavelength interval used depends on the specific pollutant gas to be detected. Typical wavelengths are:

CO	4.5 - 4.8 μm
Hydrocarbons	3.0 - 4.0 μm
	9.5 - 12.0 μm
NO	5.1 - 5.5 μm
NO ₂	3.3 - 3.6 μm
SO ₂	3.95 - 4.05 μm
	8.4 - 9.0 μm

Wavelengths must be selected on the basis of spectral band parameters and freedom from interfering species, especially water vapor.



7. 3. 7. 3c

FIGURE 7.3.7-1. Optical Layout Long-Path Gas Analyzer
Filter Correlation Receiver

Detectors

Some commercially available detectors, their operating temperature, and their regions of optimum performance are:

PbS	(193K)	2 - 3 μ m
PbSe	(193K)	2 - 5 μ m
InSb	(77K)	2 - 5 μ m
Pb(Sn, Te)	(77K)	5 - 10 μ m
Hg(Cd, Te)	(77K)	7 - 12 μ m

Characteristics values of the parameters D^* for these detectors are shown in Figure 7. 3. 7-2.

Optics

Entrance aperture,	A_o
Entrance solid angle,	Ω_o
Optical efficiency,	η_o (net transmission)
Detector optics,	$A_d \Omega_d = A_o \Omega_o$ for optimum design

These optical parameters are chosen by the designer to optimize the system performance.

Electronics

Electronic efficiency, η_e

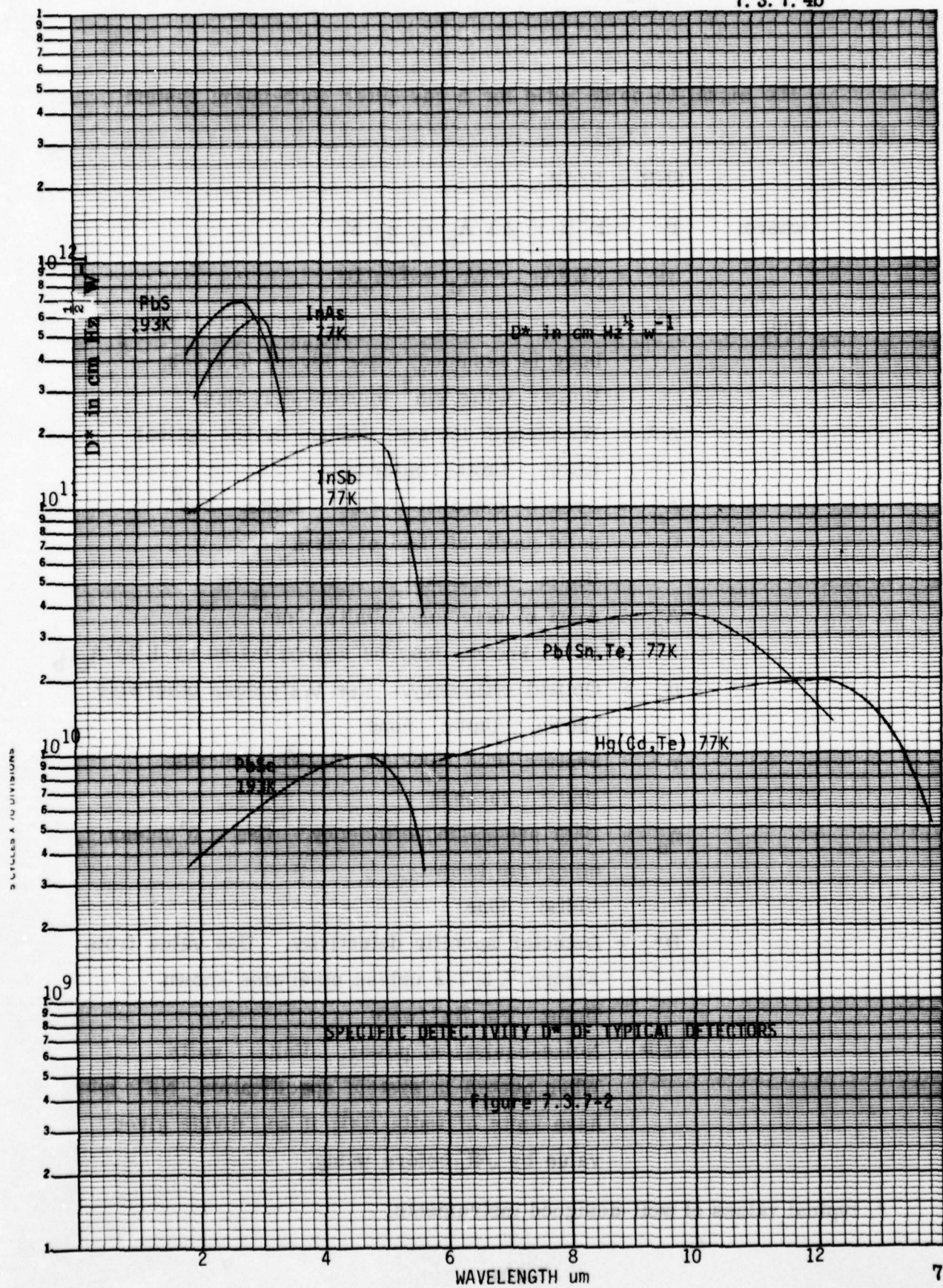
The electronic efficiency is the reduction in signal-to-noise due to the data processing. It may be appreciably less than unity even for a detector-noise-limited system.

Electronic Bandpass, Δ_f

Generally $\Delta_f = 1/4 t_c$ where t_c is the 0-63% time constant of the system readout, however, this can vary with electronics design.

7. 3. 7. 4 Theoretical Performance Prediction

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical model.



The signal-to-noise ratio for a gas filter correlation system is:

$$\text{SNR} = P/dP$$

where: $P = N^0(\lambda, \tau) \Delta\lambda A_o \Omega_o \eta_o M$

$$dP = \text{NEP}/\eta_e = (A_d/4\tau)^{1/2}/\eta_e D^*$$

and: N^0 = Source spectral radiance, normally a black-body is assumed. See Figure 7. 3. 7-3.
Units: watts/cm² micron-steradian.

$\Delta\lambda$ = Wavelength interval defined by the optical filter. Units: microns

A_o = Area of entrance optics. Units: cm²

Ω_o = Solid angle of field of view.
Units: steradians

A_d = Area of detector. Units: cm²

If not known, may be approximated by $1.59^* A_o \Omega_o$

η_o = Optical efficiency. Use 0.1* unless otherwise known. Units: none

τ = System time constant, 0-63% response.
Units: seconds

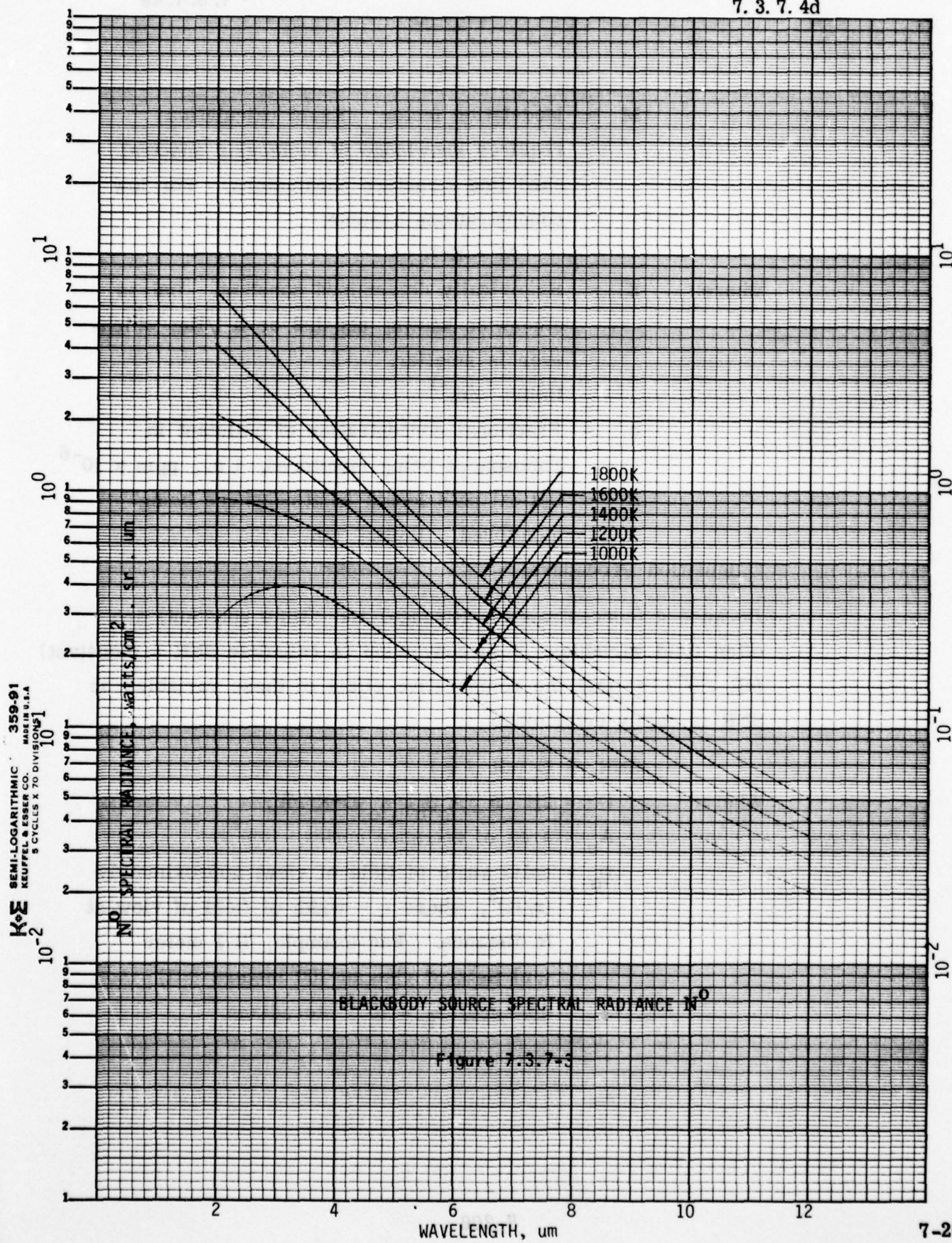
η_e = Data processing efficiency. Use 0.3* unless otherwise known.
Units: none

D^* = Detector specific detectivity. Use value from Figure 7. 3. 7-2 unless otherwise known.
Units: cm Hz^{1/2}/watt

NEP = Noise-equivalent power. Units: watts.

When quoted in system specification, NEP may have units of watts/Hz^{1/2}; if so, divide given value by $\sqrt{4C}$ before using.

* typical values of well-designed instruments.



M = Modulation factor. Exact calculation requires knowledge of molecular spectral band fine structure parameters. For low concentrations assume:

$$M \approx KcR$$

where: **K** = Empirically determined constant. Unless otherwise known, use 1.0 or $0.1/Rc$: whichever is smaller.

Units: cm^{-1}

c = Fractional concentration of pollutant in atmosphere being monitored, i.e., $\text{ppm} \times 10^{-6}$

R = Optical path length in atmosphere being monitored. Units: cm

Calculation Procedure:

Because **c** (concentration), **R**(range) and τ (time constant) are often field variables, it is convenient to calculate $\text{SNR} = (\text{constant}) (cR \sqrt{\tau})$ so that the comparative effect of these variables on SNR is easily determined.

$$\text{SNR} = G (cR \sqrt{\tau})$$

Where:

$$G = 2N^0 \Delta \lambda A_o \Omega_o \eta_o \eta_e D^* K / \sqrt{A_d}$$

A_o = area of entrance optics, (cm^2)

Ω_o = solid angle of field of view; approximately $(r/R)^2$, where **r** = width of field of view at **R** distance. For example, if 1 meter (=r) field of view at 100 meters (=R) distance, $\Omega_o = 10^{-4}$ steradians.

Analytical Determination of SNR

The above equation can be used to calculate a predicted value of SNR. Unless otherwise known the following values can be assumed for the variables defined above:

A_o = area of entrance optics, (cm^2)

Ω_o = solid angle of field of view; approximately $(r/R)^2$, where r = width of field of view at R distance. For example, if 1 meter ($=r$) field of view at 100 meters ($=R$) distance, $\Omega_o = 10^{-4}$ steradians.

N^o : assume Figure 7. 3. 7-4

$\Delta\lambda$: assume $0.1 \mu\text{m}$

A_d : assume $1.59 A_o \Omega_o$

η_o : assume 0.1

η_e : assume 0.3

D^* : assume Figure 7. 3. 7-2

k : assume 1.0 or $0.1/Rc$, whichever is smaller

τ : instrument time constant, seconds

c : concentration, $\text{ppm} \times 10^{-6}$

R : range, cm

Step 1: Calculate $G = 2N^0 \Delta \lambda A_o \Omega_o \eta_o \eta_e D^* k / \sqrt{A_d}$

Use known experimental values or approximate values given above.

This value of G can now be used for various values of c , R , and t_c which are often field variables.

Step 2: To calculate SNR given c , R , t_c :

$$SNR = G c R \sqrt{t_c}$$

Step 3: To calculate c given SNR, R , t_c :

$$c(\text{ppm} \times 10^{-6}) = SNR / G R \sqrt{t_c}$$

Graphical Determination of SNR

Graphical Determination of SNR

We assume the following typical values in the calculation of G , above. Known values are always preferred over these typical values.

$$A_o = 300 \text{ cm}^2$$

$$\Omega_o = 2 \times 10^{-5} \text{ sr}$$

$$N^0 = 0.3 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ for wavelengths 3 to 6 } \mu\text{m}$$

$$0.05 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ for wavelengths 6 to 12 } \mu\text{m}$$

$$\Delta \lambda = 0.1 \mu\text{m}$$

$$A_d = 1.59 A_o \Omega_o \text{ cm}^2$$

$$\eta_o = 0.1$$

$$\eta_e = 0.3$$

$$D^* = 10^{11} \text{ cm Hz}^{\frac{1}{2}} \text{ w}^{-1} \text{ for wavelengths 3 to 6 } \mu\text{m}$$

$$2 \times 10^{10} \text{ cm Hz}^{\frac{1}{2}} \text{ w}^{-1} \text{ for wavelengths 6 to 12 } \mu\text{m}$$

$$k = 1.0$$

We leave the quantities c , R , and τ as variables.

Step 1: Calculate: cR

Assume: R , range in meters. Double distance if monostatic system with retroreflector is used. c , pollutant concentration in ppm

Result: Figure 7. 3. 7-4 gives values of the product cR in units of cm atm.

Step 2: Calculate: $cR\sqrt{t_c}$

Assume: t_c , time constant, seconds

Result: Figure 7. 3. 7-5 gives values of the product $cR\sqrt{t_c}$.

Step 3: Calculate: SNR, signal-to-noise ratio

Assume: $cR\sqrt{t_c}$ from Step 2.

Result: Figure 7. 3. 7-6 gives SNR for the two cases:

a. 3 to 6 μm wavelength

b. 6 to 12 μm wavelength

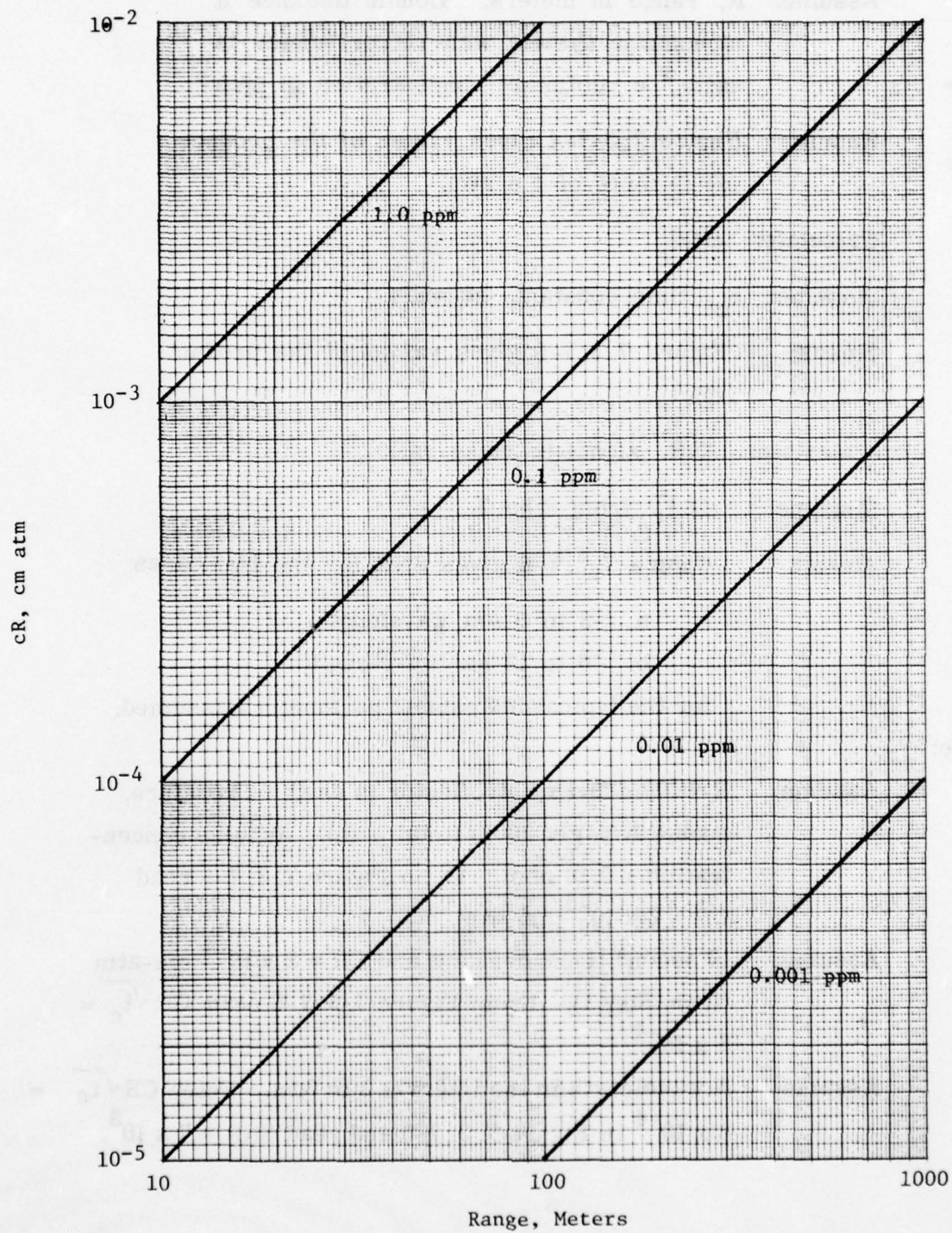
for the typical instrument parameters assumed.

Example:

Step 1: Assume: $R = 100\text{m}$ and a retroreflector is used. Therefore, double R to get 200m (total path). Assume concentration = 0.01 ppm. From Figure 7. 3. 7-4 read $CR = 2 \times 10^{-4}$ cm-atm.

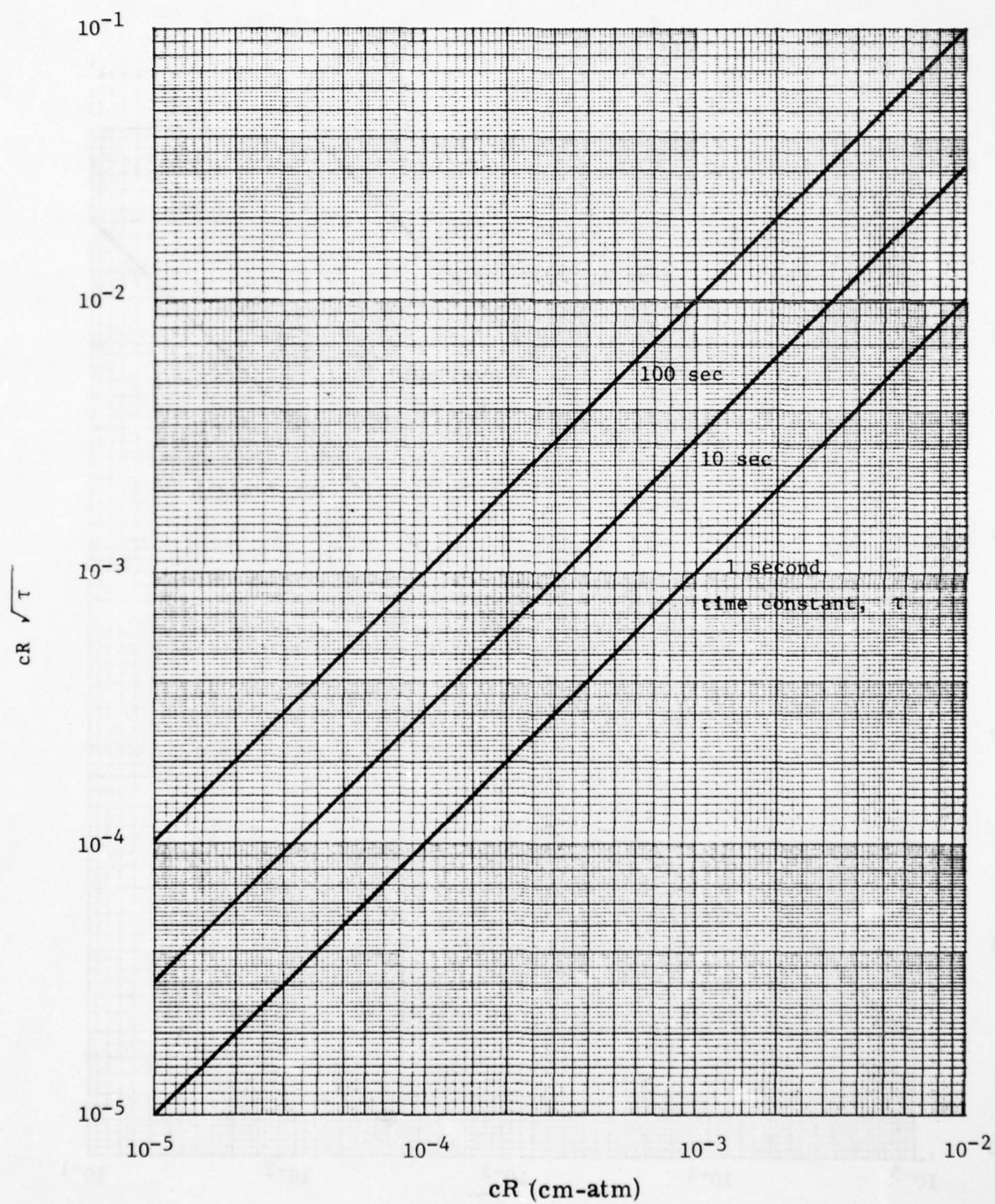
Step 2: Assume: 10 second time constant and $CR = 2 \times 10^{-4}$ cm-atm (from Step 1). From Figure 7. 3. 7-5 read $CR\sqrt{t_c} = 6 \times 10^{-4}$.

Step 3: Assume: A wavelength in the interval 3 to 6 μm . Enter $CR\sqrt{t_c} = 6 \times 10^{-4}$ in Figure 7. 3. 7-6 and read $\text{SNR} = 7 \times 10^3$.



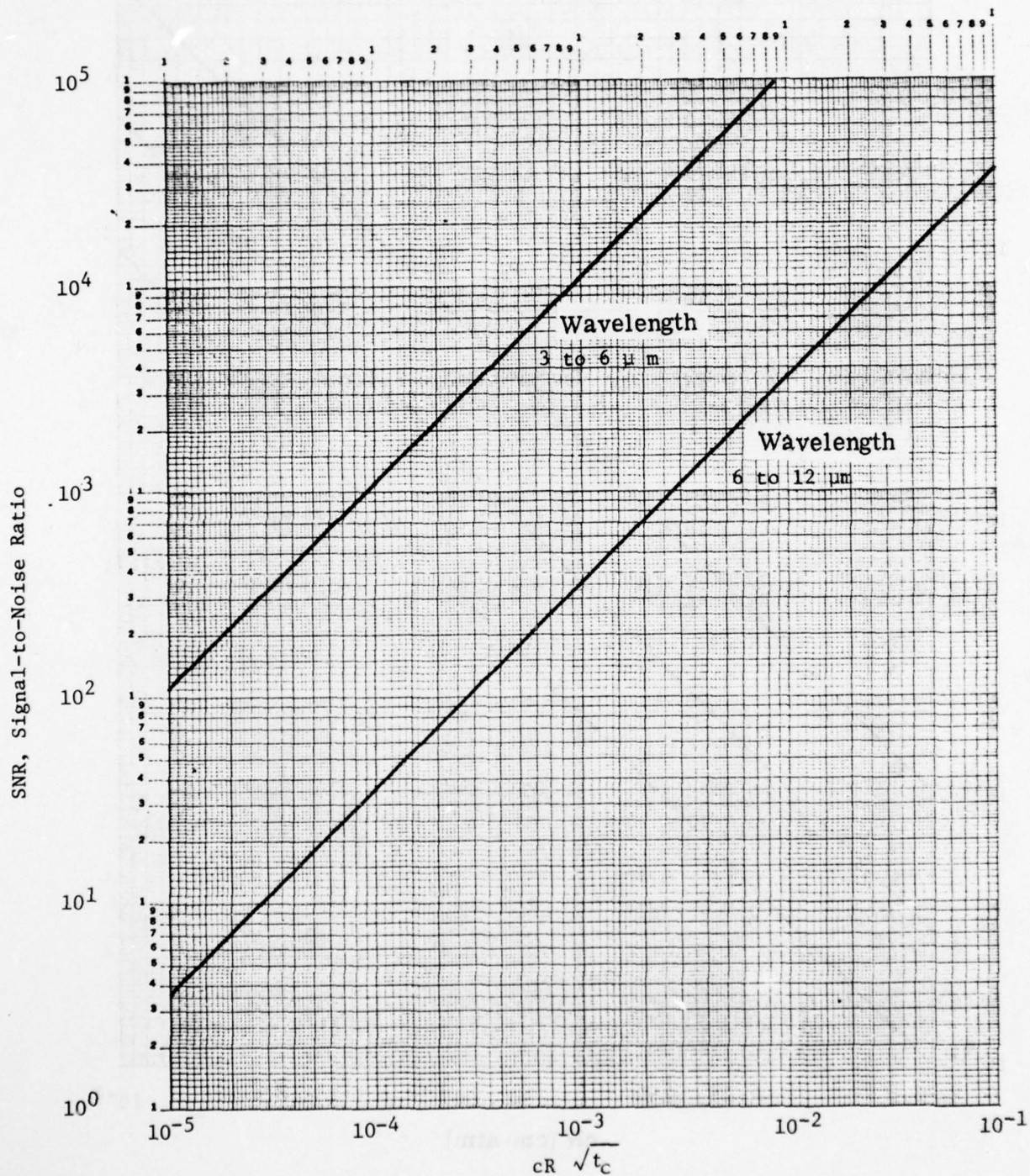
Graphical Analysis of SNR, Step 1

Fig. 7.3.7-4



Graphical Analysis of SNR, Step 2

Fig. 7.3.7-5



Graphical Analysis of SNR, Step 3

Fig. 7.3.7-6

7. 3. 7. 5 Special Performance Requirements

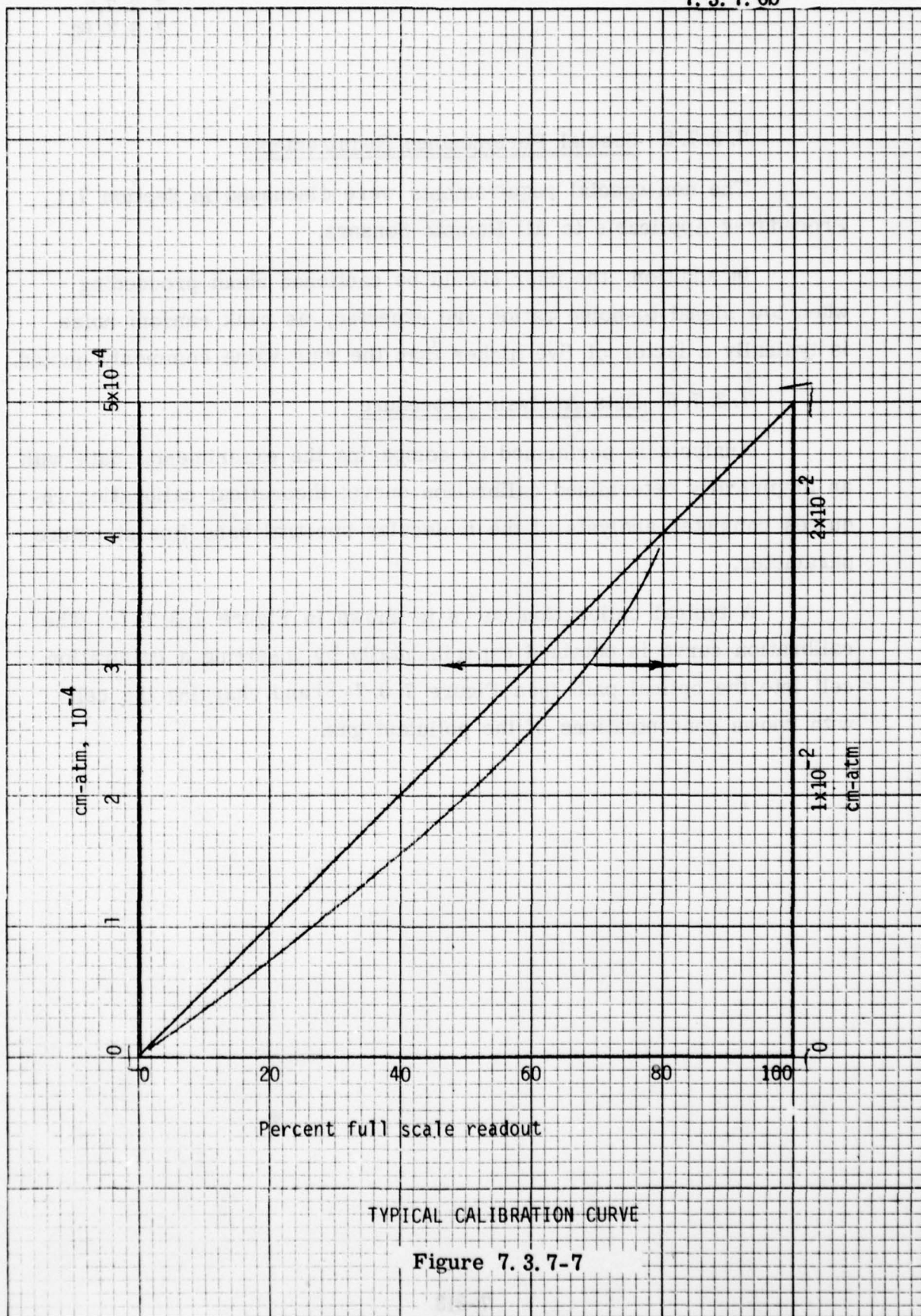
The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

In addition, the user should be cautioned about proceeding when low signal-to-noise ratios are expected, as peak random noise is typically a factor of five higher than the rms value commonly quoted.

7. 3. 7. 6 Data Analysis Procedure

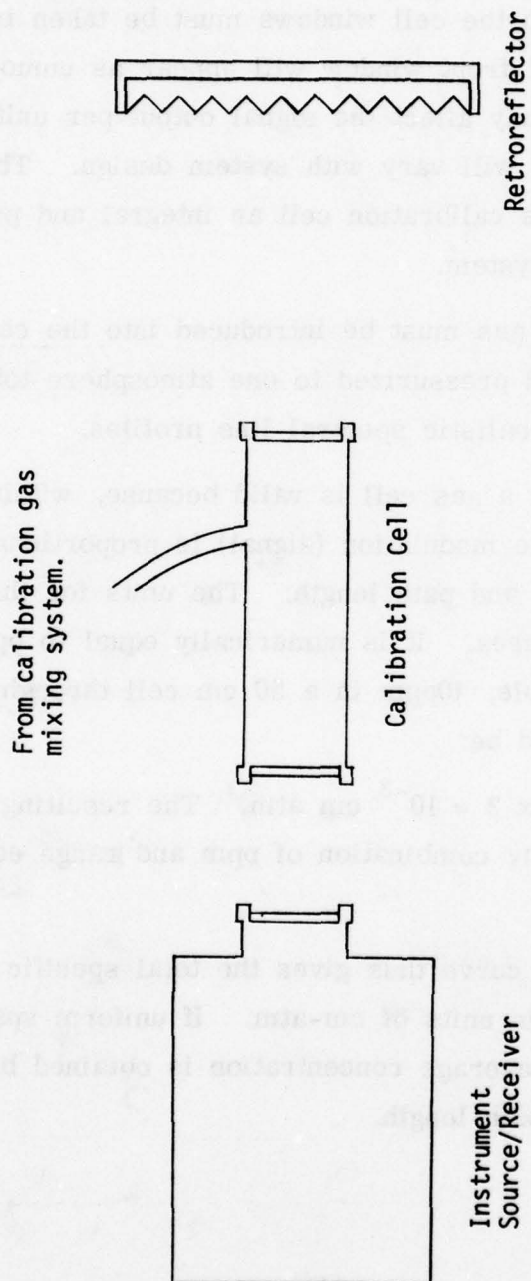
Analysis is performed by comparing the experimental data with an empirically determined calibration curve; theoretical calibration requires computer analysis of the molecular spectral band fine structure parameter.

A typical calibration curve is shown in Figure 7.3.7-7. The calibration curve is obtained experimentally by inserting a calibration cell into the optical path (see Figure 7.3.7-8) and charging the cell with known concentrations of the pollutant gas.



TYPICAL CALIBRATION CURVE

Figure 7. 3. 7-7



CALIBRATION SYSTEM

Figure 7. 3. 7-8

Precautions must be taken when using a calibration cell.

Reflections from the cell windows must be taken into account; reflections from the cell front window will appear as unmodulated source radiance which may affect the signal output per unit of calibration gas. The effect will vary with system design. This can be eliminated by making the calibration cell an integral and permanent part of the instrument system.

The calibration gas must be introduced into the cell in the proper concentration and pressurized to one atmosphere total pressure with nitrogen to cause realistic spectral line profiles.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to $\text{ppm} \times 10^{-6} \times \text{path length}$. For example, 10ppm in a 50 cm cell through which the beam passes twice would be:

$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm.}$ The resulting signal would be constant for any combination of ppm and range equalling 10^{-3} cm atm.

The calibration curve thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.

7.3.8 IR Long-Path with Broadband Source Using Filterwheel Receiver

7.3.8.1 Principle of Operation

A filterwheel receiver utilizing a broadband radiant source operates as a narrowband radiometer to measure the total absorption in an interval of the spectral band of the specific pollutant. The pollutant concentration is determined using this data plus knowledge of the path length and the instrument calibration curves.

In principle, data must be taken through two filters - one in the pollutant absorption band and one outside the band - to yield the ratio I/I_0 from which the concentration can be deduced. In practice, more than two filters are employed in order to remove the effects of superimposed absorption of other gas species.

This latter point, the lack of inherent specificity, is the cause of the performance limitation of filterwheel radiometer instruments. The current state of performance of narrowband optical filters limits the passband to not less than about one percent of the center wavelength, or about $0.05 \mu\text{m}$ at $5 \mu\text{m}$. No infrared pollutant absorption band is completely free from overlap of atmospheric lines and/or other pollutant lines, and considerable spectral interference exists between individual species that are normally present in polluted atmospheres at the spectral resolution of high quality radiometers. Water vapor is a particularly prevalent source of interference. Many filters at carefully chosen wavelengths are often incorporated to provide a set of data which in conjunction with knowledge of the spectral parameters of interfering species is used to correct for the spurious absorption.

If it is known that the circumstances do not require a high specificity instrument, a filterwheel radiometer has the positive qualities of high sensitivity, fast response, and low complexity.

7. 3. 8. 2 System Description

The system consists of a broadband radiant source covering a wavelength interval greater than the extent of the absorption band of the pollutant, and a receiver to examine the source radiation after its absorption by the intervening atmosphere. The system is bistatic; the source and receiver may be separated or they may be adjacent and a retroreflector used to define the far end of the monitored region.

The source is generally a blackbody and is chopped so that its radiation can be distinguished at the detector from spurious background radiation.

The receiver consists of a telescope or other foreoptics to collect the radiation, a filterwheel to sequentially position two or more narrow band filters into the beam, secondary optics to focus the beam onto the detector, plus the necessary electronics for control and data processing.

Figure 7. 3. 8-1 is a diagram of a filterwheel radiometer built by Bendix for EPA for measuring pollutant spectra in the 7-14 μm region (Ref. 180). Instead of a set of discrete wavelength filters, in this instrument the wavelength is scanned by rotating a continuously variable filter wheel which has a resolution of about one percent. The radiation is collected by a 28 cm aperture telescope and passed through the filter wheel to a mercury-doped germanium detector cooled by mechanical refrigeration to 28K. An on-line computer is used to analyze

the spectra in terms of pollutant concentration using regression analysis based on previous calibration data. The instrument is optically simple, but due to the poor spectral resolution the data interpretation can be difficult even with the help of the on-line computer.

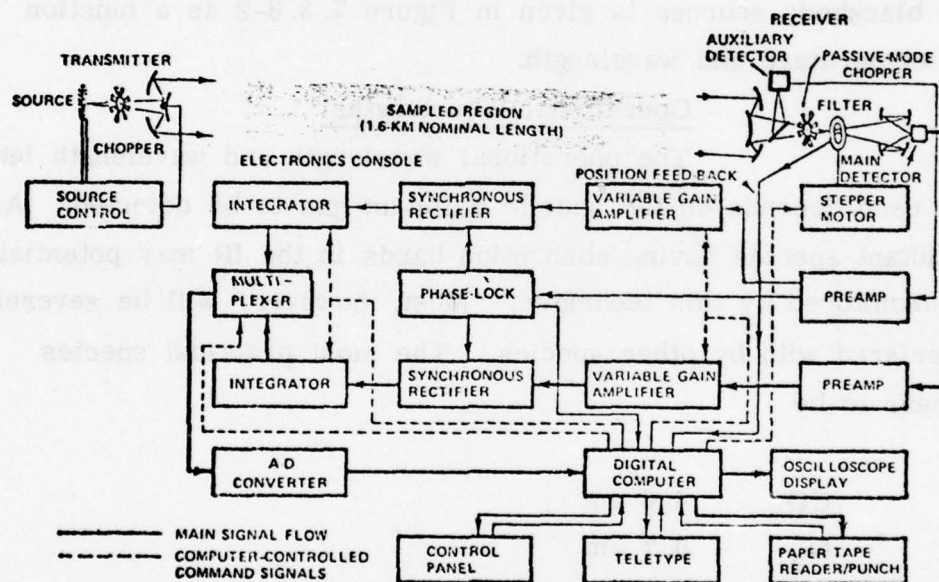


Figure 7. 3. 8-1. Block Diagram of the Bendix Filter-wheel Radiometer (Ref. 180).

7. 3. 8. 3 System Parameters

Source

Numerous commercial radiant sources are available which approximate the blackbody function over the infrared wavelength interval of interest. Temperatures available range to 1800K; 1100K is typical. Higher temperatures may not provide the expected signal improvement as they may necessitate a decrease in the instrument A Ω parameter. Spectral radiance for blackbody sources is given in Figure 7.3.8-2 as a function of temperature and wavelength.

Operational Wavelengths

The operational wavelength and wavelength interval used depends on the specific pollutant gas to be detected. All pollutant species having absorption bands in the IR may potentially be monitored by this technique. Most, however, will be severely interfered with by other species. The most practical species appear to be

CO	4.6 μm
O ₃	9.7 μm

The following table illustrates the extent of the interference which may exist, depending on the exact wavelength intervals chosen.

Table 7. 3. 8-1. Pollutants and Interfering Species (Ref. 270)

Pollutant λ (μm)	Interfering Species						
	CO_2	CO	H_2O	N_2O	CH_4	O_3	HDO
CO_2 2.1			X				
CO 4.6	X		X	X		X	
CO 2.3			X		X		X
SO_2 8.6			X	X	X	X	X
SO_2 4.0				X			
NO_2 7.6			X	X	X		X
NO_2 3.4			X		X		
NH_3 10.5	X		X	X		X	
NH_3 3.3	X		X	X	X		
NO 5.3	X	X	X				
HCHO 3.5			X	X	X		
HCl 3.3	X		X	X	X		
HF 2.7	X		X				
H_2S 3.9				X			
HNO_3 11.0	X		X	X			
CH_4 8.0			X	X			

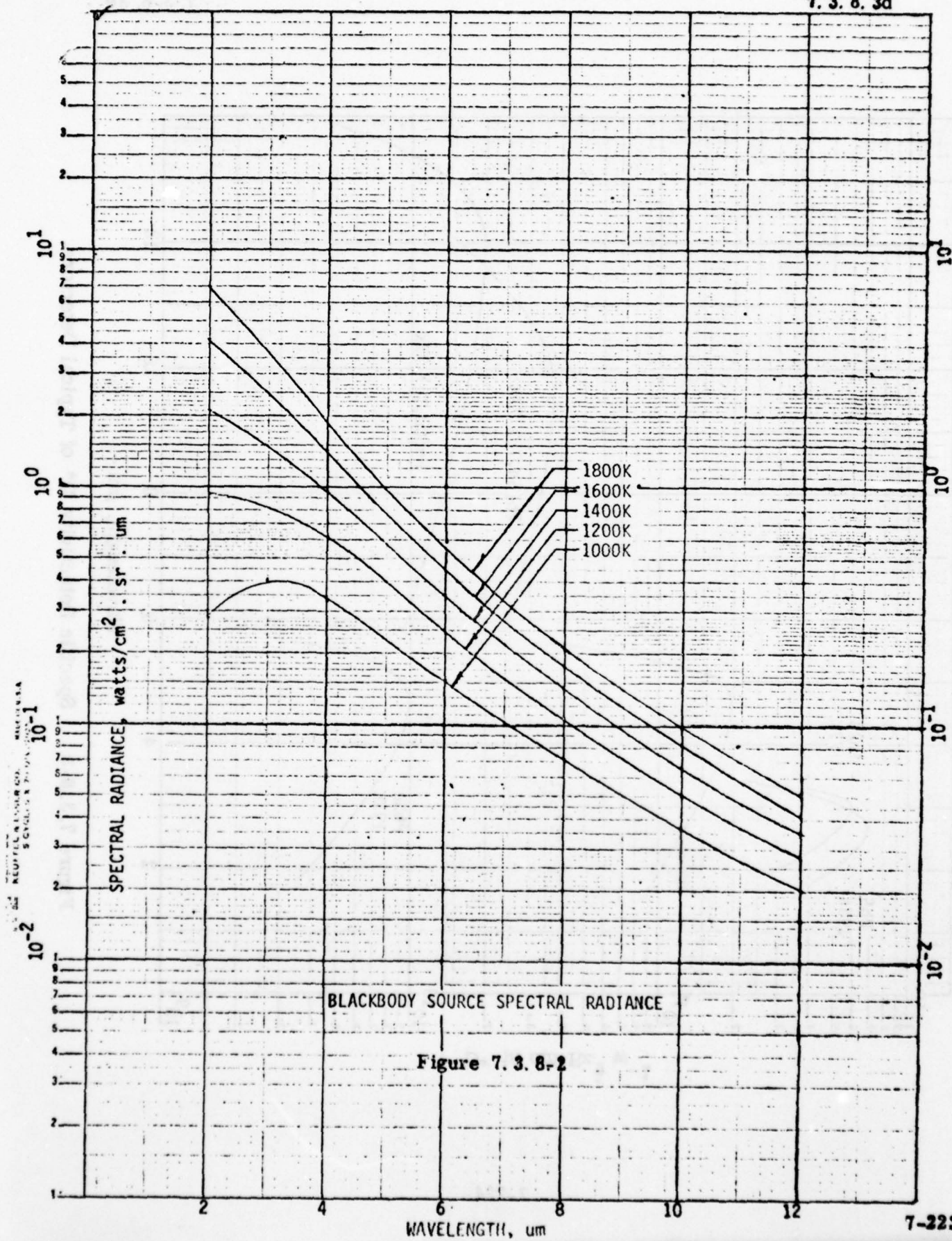
Detector

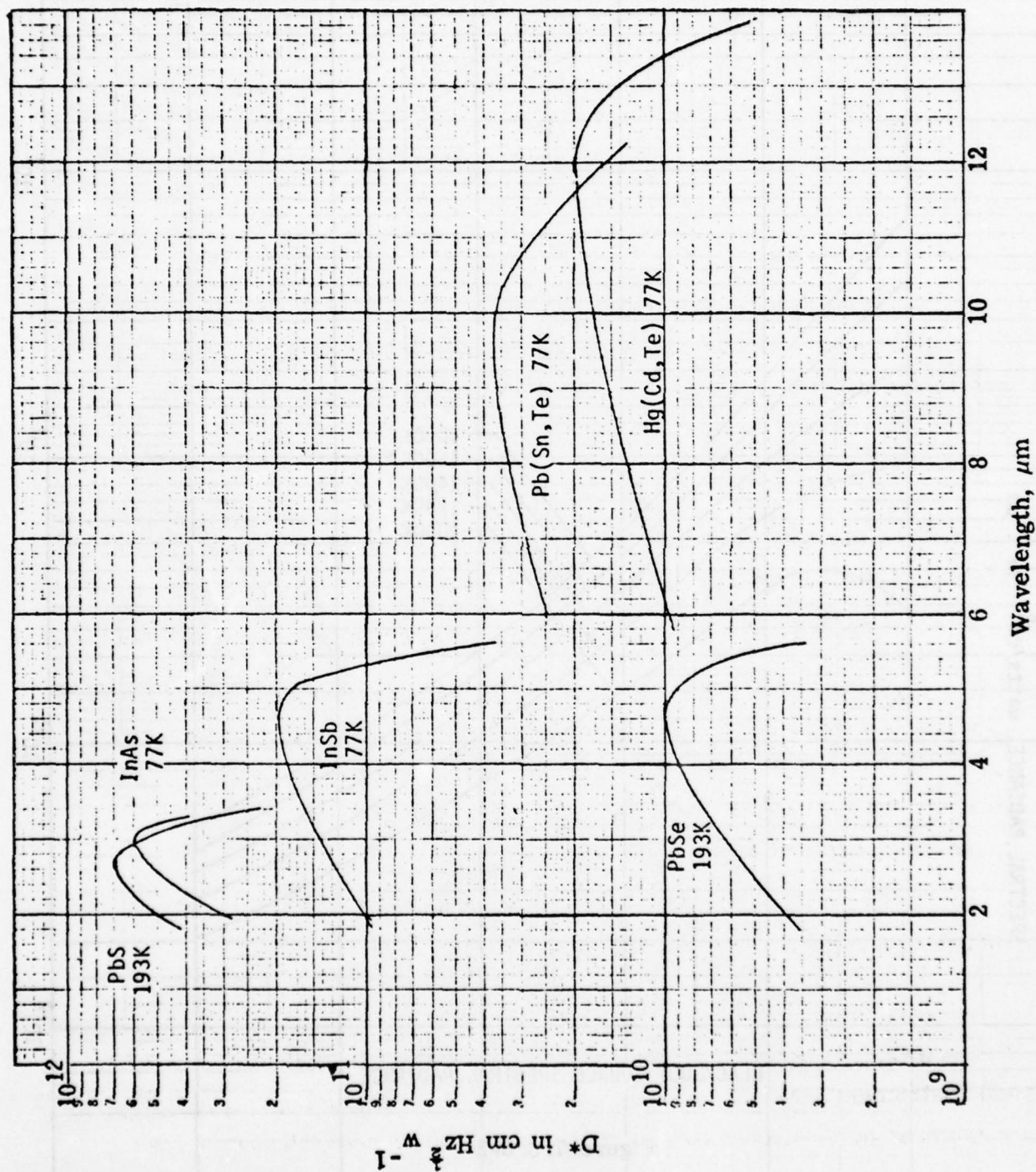
Commercially available detectors having the highest specific detectivity (D^*) at these wavelengths are

4.6 μm : Indium antimonide, InSb

9.7 μm : Lead Tin Telluride, Pb(Sn, Te)

Typical values of D^* for these and other detectors are shown in figure 7.3.8-3.



Figure 7.3.8-3 Specific Detectivity D^* of Typical Detectors.

Optics

Entrance aperture, A_o (cm²)
 Entrance solid angle, Ω_o (steradians)
 Optical efficiency, η_o (net transmission)

These optical parameters are chosen by the designer to optimize the system performance.

Electronics

Electronic efficiency, η_e

The electronic efficiency is the reduction in signal-to-noise due to the data processing. It may be appreciably less than unity even for a detector-noise-limited system.

Electronic Bandpass, Δ_f

Generally $\Delta_f = 1/4t_c$ where t_c is the 0-63% time constant of the system readout, however, this can vary with electronics design.

7. 3. 8. 4 Theoretical Performance Prediction

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical model.

From Appendix VII, the signal-to-noise ratio for a filterwheel radiometer system is:

$$SNR = P/dP$$

The numerator, P , contains the source function, the modulation function and instrument optical performance terms. The denominator dP is the instrument performance limitation assuming optimized detector-noise-limited operation.

where: $P = N^0(\lambda, T) \Delta\lambda A_o \Omega_o \eta_o M$

$$dP = NEP/\eta_e = (A_d/4\tau)^{1/2}/(\eta_e D^*)$$

and: N^0 = Source spectral radiance, normally a blackbody is assumed. See Figure 7.3.8-2.
Units: watts/cm² micron-steradian.

$\Delta\lambda$ = Wavelength interval defined by the optical filter.
Units: microns

A_o = Area of entrance optics. Units: cm².

Ω_o = Solid angle of field of view.
Units: steradians

A_d = Area of detector. Units: cm²
If not known, may be approximated by $1.59 A_o \Omega_o$

η_o = Optical efficiency. Use 0.1* unless otherwise known. Units: none

t_c = System time constant, 0-63% response.
Units: seconds

η_e = Data processing efficiency. Use 0.3* unless otherwise known.
Units: none

D^* = Detector specific detectivity. Use value from Figure 7.3.8-3 unless otherwise known.
Units: cm Hz^{1/2}/watt

NEP = Noise-equivalent power. Units: watts.
When quoted in system specification, NEP may have units of watts/Hz^{1/2}; if so, divide given value by $\sqrt{4t_c}$ before using.

*Typical values for well-designed systems.

M = Modulation factor. Exact calculation requires knowledge of the molecular spectral band parameters. If we assume that the intensity of the source is the same at the off-band and on-band measured wavelengths, the modulation factor becomes

$$M = 1 - \exp \left[- (kcR(1+kcR/4a))^{-\frac{1}{2}} \right]$$

where k = band-averaged absorption coefficient Units:
cm⁻¹ atm⁻¹

where a = band-averaged fine structure parameter Units:
none

c = Fractional concentration of pollutant in atmosphere
being monitored, i. e., ppm $\times 10^{-6}$

R = Optical path length in atmosphere being monitored.
Units: cm.

Values of k and a can be obtained from NASA CR-2324 (Reference 180).

Calculation Procedure:

We can approximate the modulation factor as

$$M = 1 - \exp(-kcR)$$

and the signal-to-noise equation becomes

$$SNR = 2N^0_{\Delta} \lambda A_o \Omega_o \eta_o \eta_e D^* M \sqrt{\tau} / \sqrt{A_d}$$

SNR values will generally be quite high with this type of instrument. The measurement should not be assumed to be accurate to better than 0.01 ppm.

Analytical Determination of SNR

The above equation can be used to calculate a predicted value of SNR. Unless otherwise known the following values can be assumed for the variables defined above:

A_o = area of entrance optics

Ω_o = solid angle of field of view; approximately $(r/R)^2$, where r = width of field of view at R distance. For example, if 1 meter ($=r$) field of view at 100 meters ($=R$) distance, $\Omega_o = 10^{-4}$ steradians.

N^o : assume Figure 7. 3. 8-2

$\Delta\lambda$: assume $0.05 \mu\text{m}$ (typical value for well-designed system)

A_d : assume $1.59 A_o \Omega_o$

η_o : assume 0.1

η_e : assume 0.3

D^* : assume Figure 7. 3. 8-3

k : assume $0.014 \text{ cm}^{-1} \text{ atm}^{-1}$ for CO at $4.6 \mu\text{m}$

assume $0.021 \text{ cm}^{-1} \text{ atm}^{-1}$ for O_3 at $9.7 \mu\text{m}$

t_c : instrument time constant, seconds

c : concentration, $\text{ppm} \times 10^6$

R : range, cm

it is convenient to calculate SNR in two steps.

$$\text{SNR} = G (M\sqrt{\tau})$$

where $G = 2N^0 \Delta\lambda A_o \Omega_o \eta_o \eta_e D^* / \sqrt{A_d}$

$$M = 1 - \exp(\bar{k}cR)$$

Step 1: Calculate G

Use known experimental values or approximate values given above.

This value of G can now be used for various values of c, R, and τ , which are often field variables.

Step 2: Calculate $SNR = G (1 - \exp(\bar{k}cR)) \sqrt{t_c}$

Use various anticipated field values of c, R and τ . Use values of \bar{k} given above.

Graphical Determination of SNR

We assume the following typical values

$$A_o = 500 \text{ cm}^2$$

$$\Omega_o = 10^{-4} \text{ sr}$$

$$N^0 = 0.5 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ at } 4.6 \mu\text{m (CO)}$$

$$0.05 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ at } 9.7 \mu\text{m (O}_3\text{)}$$

$$\Delta\lambda = 0.05 \mu\text{m}$$

$$A_d = 1.59 A_o \Omega_o \text{ cm}^2$$

$$\eta_o = 0.1$$

$$\eta_e = 0.3$$

$$D^* = 10^{11} \text{ cm HI}^{\frac{1}{2}} \text{ w}^{-1}$$

We leave the quantities c, R, and t_c as variables.

Step 1: Calculate: $M = 1 - \exp(\bar{k}cR)$

Assume: Value of pollutant concentration, ppm
Range, meters

Result: Figure 7. 3. 8-4 gives M for CO and O_3 as a function of c and R.

Step 2: Calculate: $SNR = GM\sqrt{t_c}$

Assume: Value of G based on assumed experimental values above.

t_c , time constant, seconds

M, modulation factor, from Step 1

Result: Figure 7. 3. 8-5 and 7. 3. 8-6 give values of SNR for, respectively, CO and O_3 for values of M and t_c .

7. 3. 8. 5 Special Performance Requirements

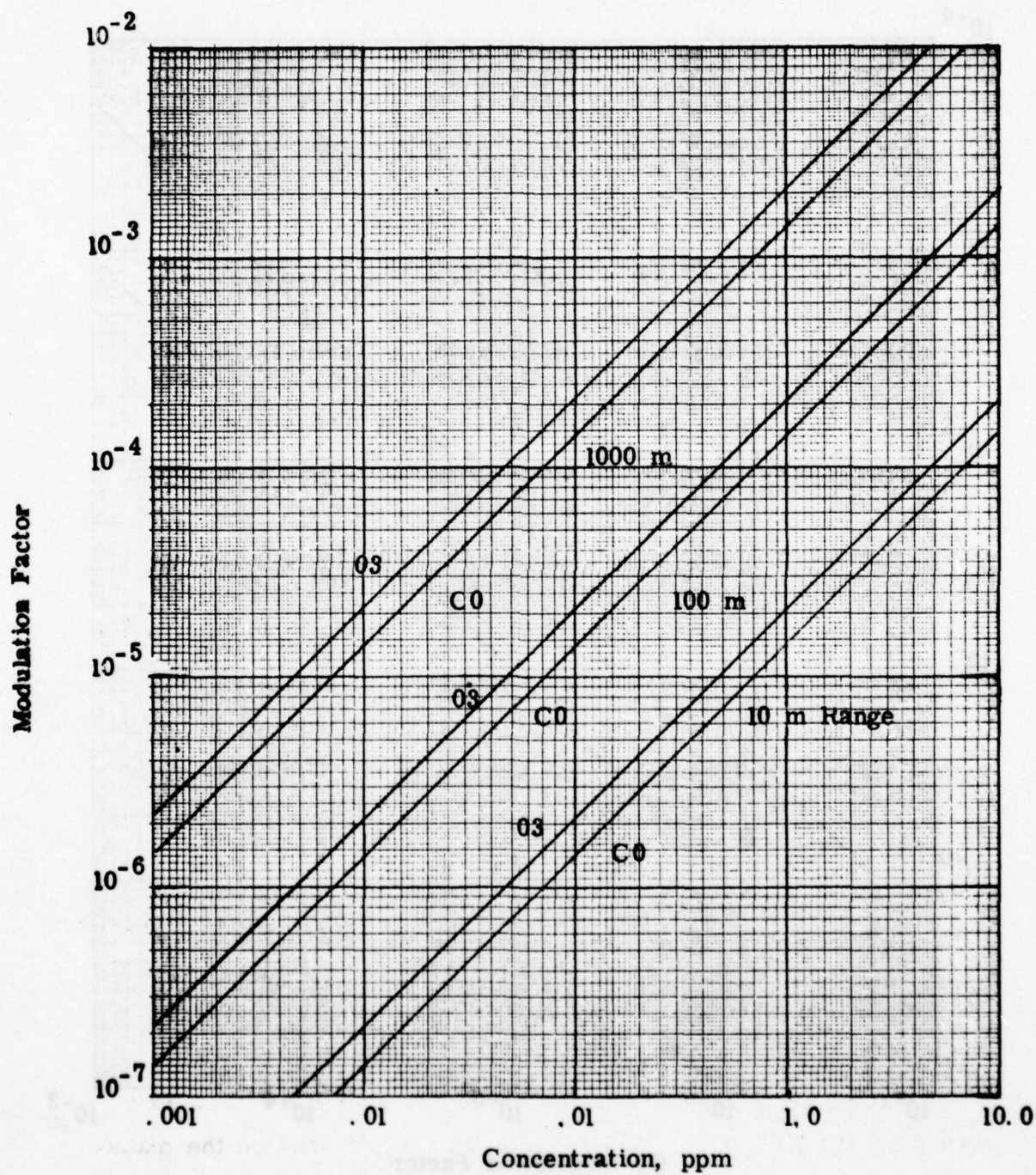
The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

In general, no special requirements are required by radiometers. Special requirements due to a particular instrument design should be noted by the manufacturer.

7. 3. 8. 6 Data Analysis Procedure

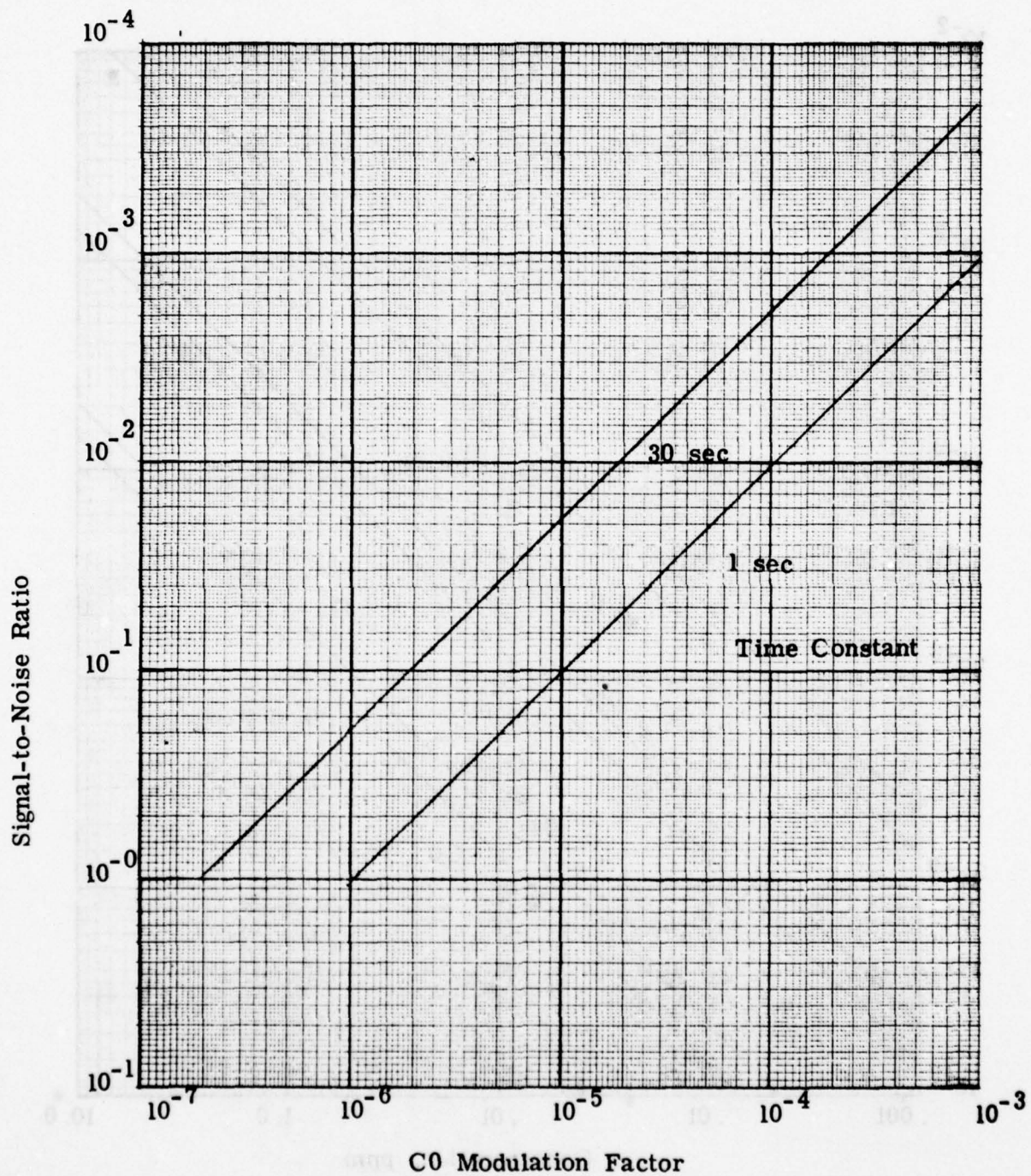
In its simplest form, data analysis is performed by comparing the experimental data with an empirically determined calibration curve. This can result in large errors due to spurious signals caused by overlapping absorption bands of other species.

The analysis procedure to correct this problem must be detailed by the instrument manufacturer and will depend on the manufacturer's ingenuity, the exact wavelengths at which the measurements



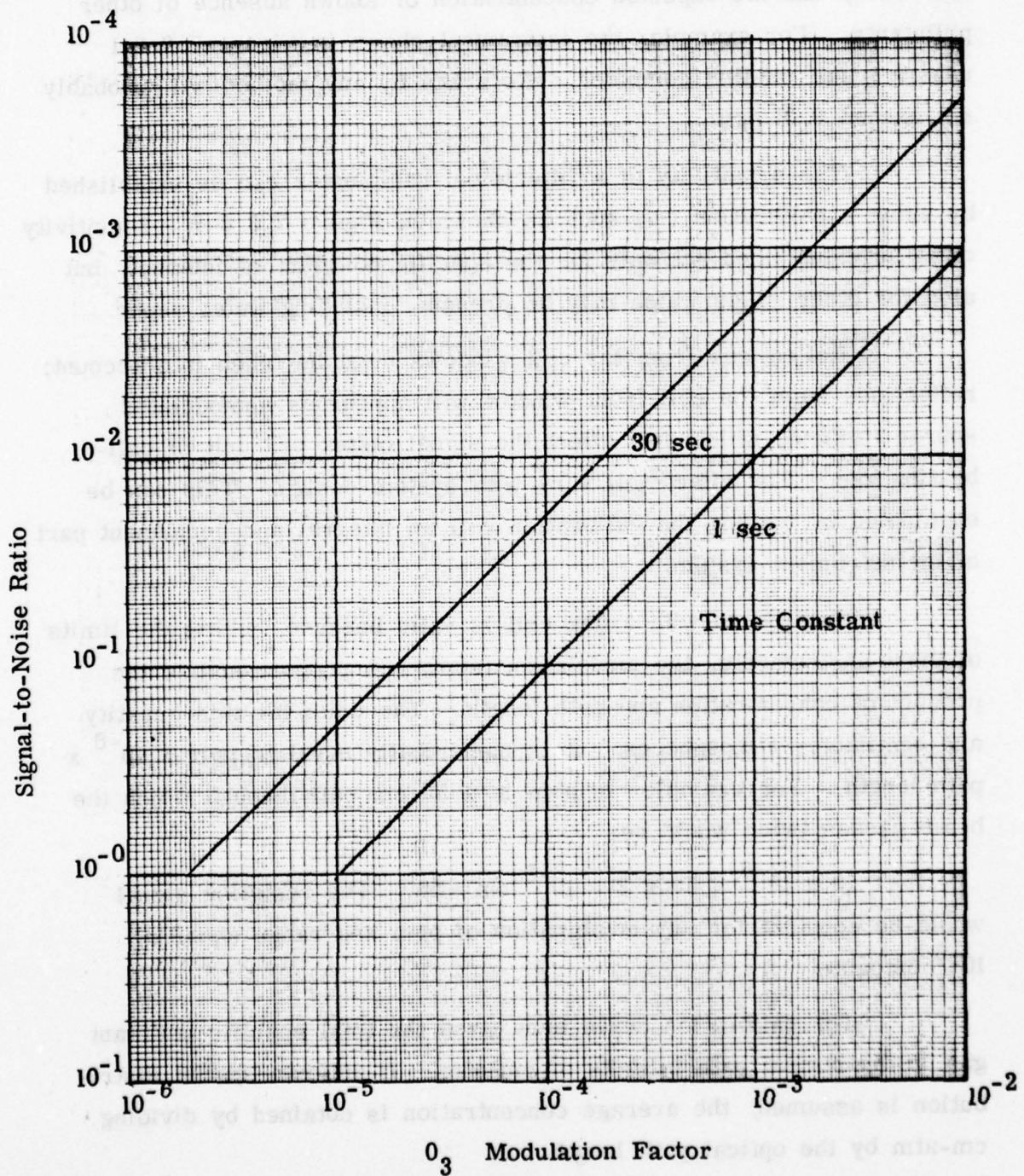
Graphical Analysis - Step 1

Figure 7.3.8-4



Graphical Analysis - Step 2

Figure 7. 3. 8-5



O_3 Modulation Factor
Graphical Analysis - Step 2
Figure 7. 3. 8-6

are taken, and the expected concentration or known absence of other pollutants. For example, the instrument shown in Figure 7. 3. 8-1 uses a small on-line computer. Accuracy by any method will probably not exceed 0. 01 ppm.

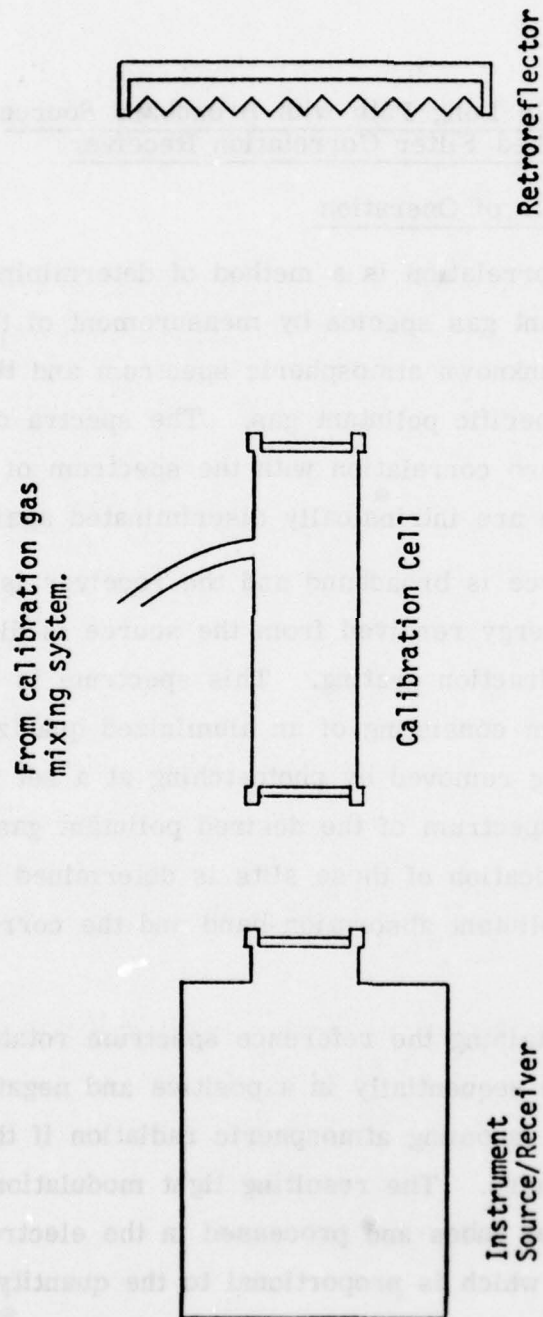
The sensitivity of a filterwheel radiometer can be established by using a calibration cell such as shown in Figure 7. 3. 8-7. Sensitivity must be established not only for the specific pollutant of interest, but also for other gases which may be present, including water vapor.

Reflections from the cell windows must be taken into account; reflections from the cell front window will appear as unmodulated source radiance which may affect the signal output per unit of calibration gas. The effect will vary with system design. This can be eliminated by making the calibration cell an integral and permanent part of the instrument system.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to $\text{ppm} \times 10^{-6} \times \text{path length}$. For example, 10 ppm in a 50 cm cell through which the beam passes twice would be:

$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm}$. The resulting signal would be constant for any combination of ppm and range equalling 10^{-3} cm atm .

The calibration curve thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.



CALIBRATION SYSTEM

Figure 7. 3. 8-7

7.3.9 UV/Visible Long Path with Broadband Source
and Matched Filter Correlation Receiver

7.3.9.1 Principle of Operation

Matched filter correlation is a method of determining the concentration of a pollutant gas species by measurement of the correlation between the unknown atmospheric spectrum and the known spectrum of the specific pollutant gas. The spectra of other gases have near zero correlation with the spectrum of this particular species and so are intrinsically discriminated against.

The radiant source is broadband and the receiver is dispersive. The radiant energy received from the source is dispersed into a spectrum by a diffraction grating. This spectrum is focused onto a reference spectrum consisting of an aluminized quartz disk with the aluminum coating removed by photoetching at a set of precise wavelengths in the spectrum of the desired pollutant gas species. The spectral width and location of these slits is determined by computer modelling of the pollutant absorption band and the correlation process.

As this disk containing the reference spectrum rotates, the slit arrays will correlate sequentially in a positive and negative sense with the spectrum of the incoming atmospheric radiation if that species is present in the atmosphere. The resulting light modulations are detected by photomultiplier tubes and processed in the electronics to produce a voltage output which is proportional to the quantity (ppm-meters) of the pollutant in the measured path.

In principle, this technique is similar to gas filter correlation, described in 7. 3.7 and 7. 3.10 of this report, except that gas filter correlation uses a sample of the gas as a wavelength-selective absorber in a nondispersive optical system.

7. 3. 9. 2 System Description

The system consists of a source and a receiver. The source may be at the opposite end of the test region, or it may be adjacent to the receiver and a retroreflector used to define the test region extremity. In this latter case the sensitivity is increased because the path length through the atmosphere is doubled.

The source must be chopped to provide a means by which the electronics can discriminate against the spurious signal component due to scattered and reflected sunlight, which can be strong at these wavelengths.

Figures 7. 3. 9-1 and -2 are the schematic and photograph of a matched filter instrument. The specific instrument shown is designed to measure two gases simultaneously and so contains two diffraction gratings and detectors.

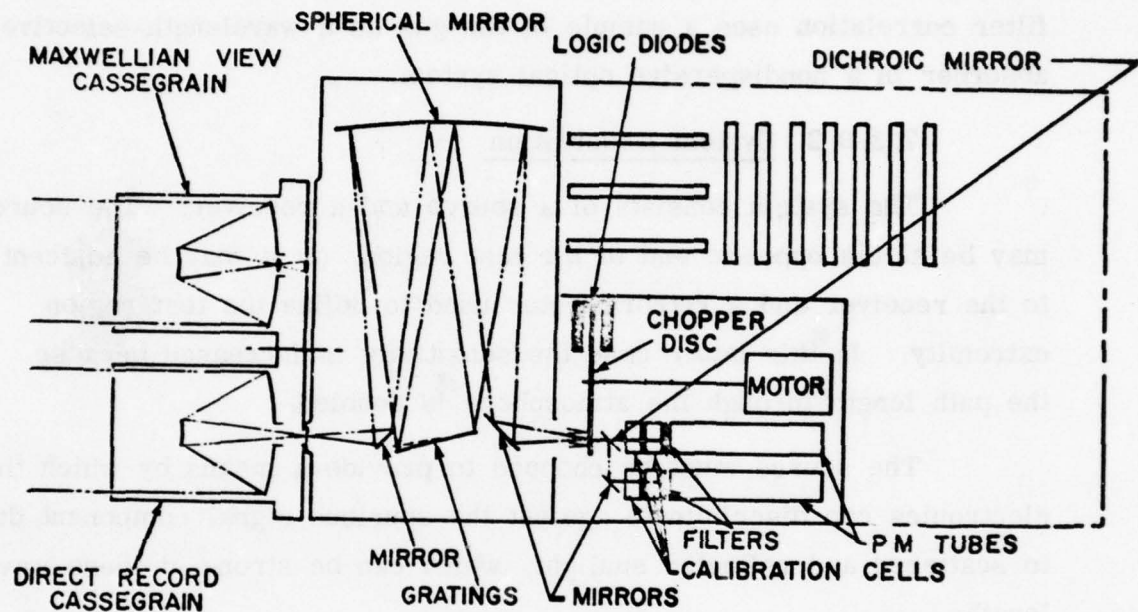


Figure 7. 3. 9-1. Matched Filter Correlation Instrument Diagram,
Dual Gas Model

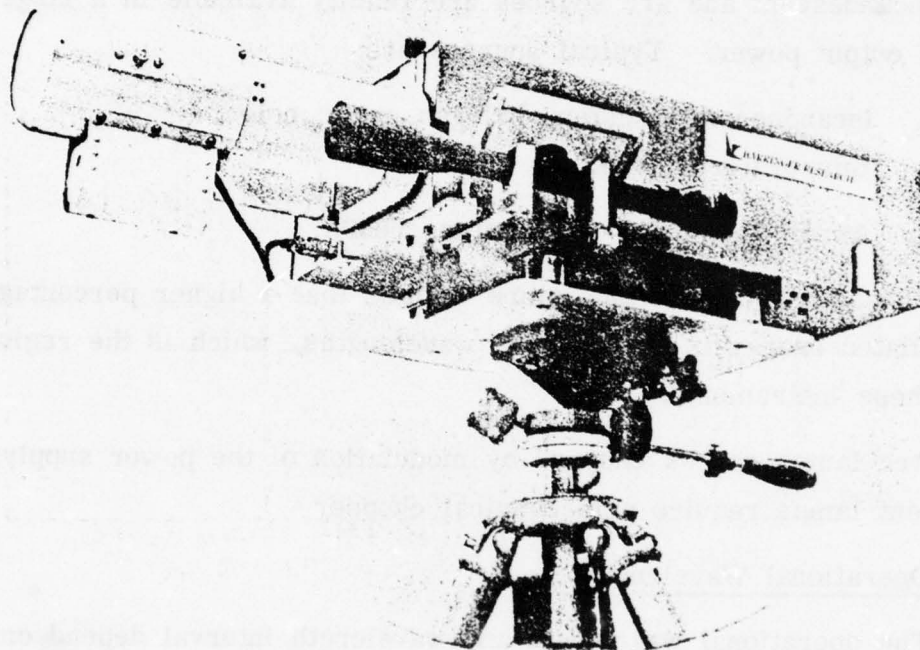


Figure 7. 3. 9-2. Matched Filter Correlation Instrument

7. 3. 9. 3. System Parameters

Source

Incandescent and arc sources are readily available in a large variety of output power. Typical sources are:

1. Incandescent tungsten, halogen cycle; color temperature 3000K.
2. Xenon arc; color temperature 6000K.

The higher color temperature implies that a higher percentage of the radiated energy is in the short wavelengths, which is the region used by these instruments.

Arc lamps can be chopped by modulation of the power supply; incandescent lamps require a mechanical chopper.

Operational Wavelengths

The operational wavelength and wavelength interval depend on the specific pollutant gas to be detected.

Not all pollutants are suitable for matched filter correlation detection. To date, the measurement of two gases have been shown to be feasible by this technique:

SO₂ 280-315 nm

NO₂ 413-450 nm

Detector

Photomultiplier tubes are the detectors best suited for this wavelength region. Many varieties are available for optimizing the instrument design. Those having an S-5 response function have peak

response in these wavelength regions, although other response functions may be better suited to a particular instrument.

Optics

Entrance aperture,	A_o (cm^2)
Entrance solid angle,	Ω_o (steradians)
Optical efficiency,	η_o (net transmission)

These optical parameters are chosen by the designer to optimize the system performance.

7. 3. 9. 4. Theoretical Performance Predictions

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical model.

From Appendix VII, the signal-to-noise ratio for a matched filter correlation system is:

$$\text{SNR} = P/dP$$

The numerator, P , contains the source function, the modulation function and instrument optical performance terms. The denominator dP is the instrument performance limitation assuming optimized operation.

The signal for the matched filter correlation system is given by

$$P = \eta_o A_o \Omega_o N n \Delta \lambda M \lambda / hc$$

where

η_o = optical efficiency

A_o = entrance aperture

Ω_o = entrance solid viewing angle

N = source radiance

n = number of slits in reference spectrum

$\Delta \lambda$ = width of slits in reference spectrum

M = modulation coefficient; see below

λ = center band wavelength

h = Planck's constant

c = speed of light

The modulation coefficient is given by

$$M = e^{-a_1 CR} - e^{-a_2 CR}$$

where

a_1 = average minimum atmospheric absorption coefficient across the slits.

a_2 = average maximum atmospheric absorption coefficient across the slits.

C = concentration

R = range

The system will in general be shot-noise limited with the noise level given by

$$dP = (\eta_o A_o \Omega_o N n \Delta \lambda M_1 \lambda / hc)^{1/2}$$

where

$$M_1 = (e^{-a_1} + e^{-a_2})/2$$

and the other quantities are as previously defined.

The signal-to-noise ratio is therefore

$$SNR = (\eta_o A_o \Omega_o N n \Delta \lambda \lambda / hc)^{1/2} (M/M_1)^{1/2}$$

Calculation Procedure

The values of SNR determined here are very high due to the ideal system assumed. In practice, the noise will be significantly higher due to interfering gas species, spectral structure in the source radiance and non-ideal instrument parameters.

Analytical Determination of SNR

For computational convenience only, the parameter IP is introduced.

Step 1: Calculate the instrument parameter:

$$IP = (\eta_o A_o \Omega_o N^o n \Delta \lambda \lambda / hc)^{1/2}$$

Typical values may be assumed. Known values are always to be preferred over these typical values.

$$\eta_o = 0.01$$

$$A_o = 100 \text{ cm}^2$$

$$\Omega_o = 10^{-5} \text{ steradians}$$

$$n \Delta \lambda = 15 \text{ nm}$$

$$N = 1.0 \text{ w/sr cm}^2 \text{ nm at 300 nm (SO}_2\text{)}$$

$$N = 3.0 \text{ w/sr cm}^2 \text{ nm at 430 nm (NO}_2\text{)}$$

$$\lambda / hc = 1.5 \times 10^{18} \text{ at 300 nm}$$

$$\lambda / hc = 2.2 \times 10^{18} \text{ at 430 nm}$$

Hence,

$$IP = 1.5 \times 10^7 \text{ for SO}_2$$

$$IP = 3.1 \times 10^7 \text{ for NO}_2$$

Step 2: Calculate the modulation parameter:

$$\left(\frac{M}{M_1^{1/2}} \right) = \frac{(e^{-a_1 CR} - e^{-a_2 CR}) 1.414}{(e^{-a_1 CR} + e^{-a_2 CR})^{1/2}}$$

Using the approximate gas parameter values:

$$a_1 = 7 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for SO}_2$$

$$7 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for NO}_2$$

$$a_2 = 10 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for SO}_2$$

$$15 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for NO}_2$$

These values of a_1 and a_2 are highly dependent on the particular instrument design.

The other parameters are the expected field values:

$$C = \text{pollutant concentration, ppm} \times 10^6$$

$$R = \text{measurement range, cm}$$

Step 3: Calculate the anticipated signal-to-noise:

$$SNR = IP \left(\frac{M}{M_1^{1/2}} \right)$$

Graphical Determination of SNR

Step 1: Calculate: Total pollutant in test path.

 Assume: Known length of test path, meters.
 Anticipated pollutant concentration, ppm.

 Result: Plot in Figure 7. 3. 9-3 gives total pollutant
 in units of cm-atm.

Step 2: Calculate: Anticipated SNR.

 Assume: Total pollutant in cm-atm (Step 1) assumed
 typical instrument parameters as given in
 Analytical Determination of SNR.

 Result: Plot in Figure 7. 3. 9-4 gives anticipated SNR
 as a function of total pollutant.

Example: In Step 1 of the Analytical Determination of SNR, parameters are given which are typical of a well-designed system. In the absence of actual instrument values, these typical values may be assumed. Using these typical values, the parameter IP is calculated to be 1.5×10^7 for SO_2 and 3.1×10^7 for NO_2 . If actual values are known, this parameter should also be calculated using the known values.

In Figure 7. 3. 9-4, the SNR curves assume the typical values of IP. If actual values of IP are known, the SNR should be corrected as follows:

$$\text{SNR (actual)} = \text{SNR (typical)} \frac{\text{IP (actual)}}{\text{IP (typical)}}$$

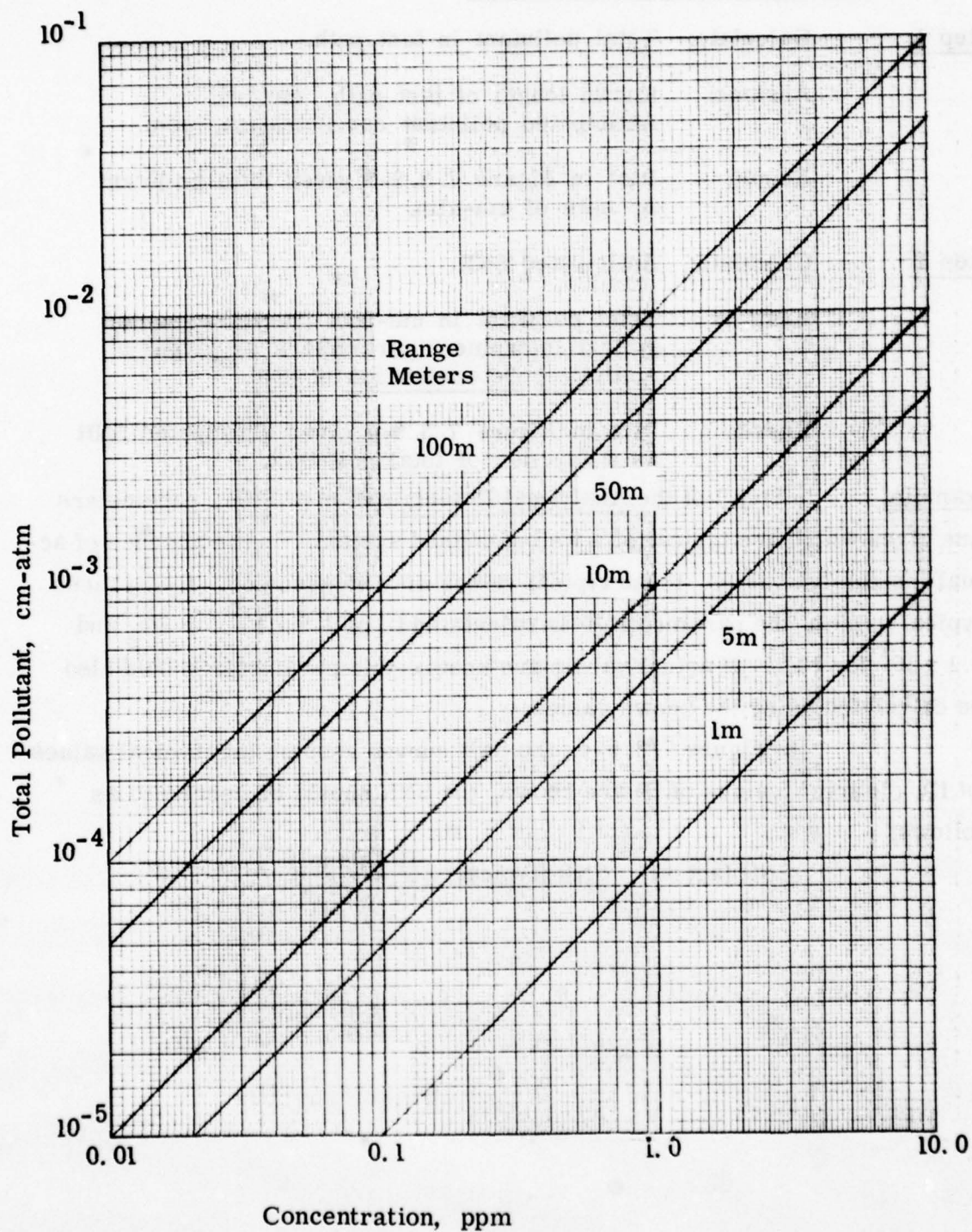


Figure 7. 3. 9-3. Graphical SNR Determination - Step 1

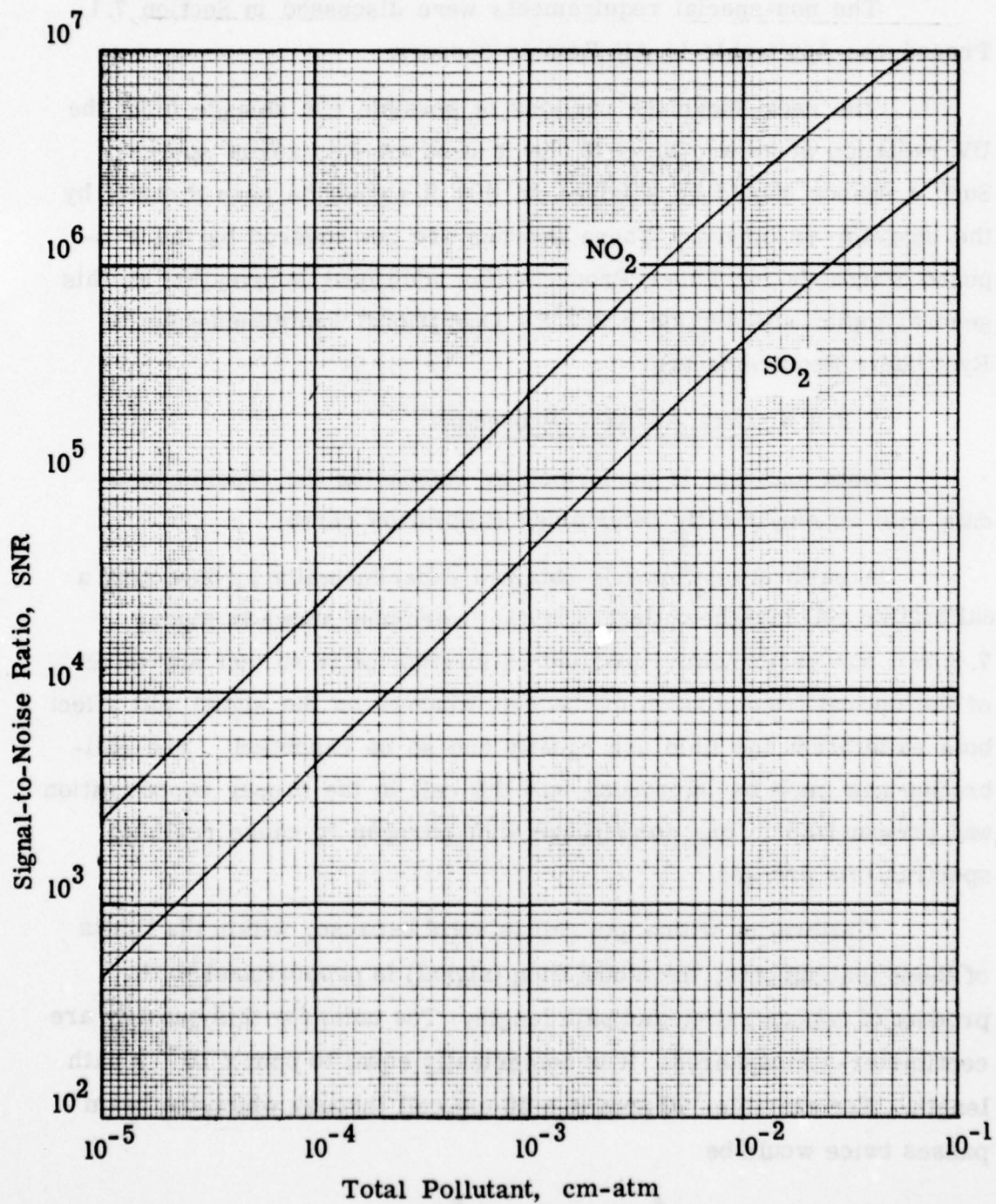


Figure 7. 3. 9-4. Graphical SNR Determination - Step 2

7. 3. 9. 5 Special Performance Requirements

The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

The user should be cautious of possible eye damage from the UV radiation of an arc lamp if one is used as the radiant source. Such a source should be shielded so that it cannot be seen directly by the operator or others. These sources are not covered by the Proposed Standards for Laser Products (for additional information on this general topic, see Section 6.2.2.2 - Operational Limitations due to Eye Safety Requirements).

7. 3. 9. 6 Data Analysis Procedure

Data analysis is performed by comparing the experimental data with an empirically determined calibration curve.

A calibration curve is obtained experimentally by inserting a calibration cell into the optical path (the instrument shown in Figure 7.3.9-1 has permanently installed calibration cells so that any effect of the optical transmission of the cell windows on the signal will affect both calibration and field use equally and so be cancelled. The calibration gas must be introduced into the cell in the proper concentration and pressurized to one atmosphere with nitrogen to cause realistic spectral line profiles.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to $\text{ppm} \times 10^{-6} \times \text{path length}$. For example, 10 ppm in a 50 cm cell through which the beam passes twice would be

$$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm}$$

The resulting signal would be constant for any combination of ppm and range equaling 10^{-3} cm-atm.

The calibration thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.

Because of the uncertain path length due to scattering by atmospheric aerosols, the use of instruments operating at ultraviolet wavelengths may be limited in an airport environment to short range operation. Analysis of calibration accuracy in the presence of significant scattering is a very complex problem and depends on parameters values of the particular aerosol environment which are generally not known.

7. 3. 10 Passive Downward-Looking Monitor Using Gas Filter Correlation Receiver

This monitor was not found acceptable in the Selection and Ranking, Section 6. 2. 2. 1. The Data Validation section is included here because the discussion is pertinent to passive systems in general, in particular to the passive upward-looking systems of Section 7. 4.

7. 3. 10. 1 Principle of Operation

Gas filter correlation is a method of determining the concentration of pollutant gas species by measuring the correlation between the unknown atmospheric spectrum and the spectrum of a known sample of the specific pollutant gas which is contained in the instrument. The spectra of other gases have near zero correlation with the spectrum of this particular species and so are intrinsically discriminated against.

The radiant source is broadband and the receiver is non-dispersive. The radiant energy received from the source is passed alternately through the sample of the particular species and through a neutral absorber having the same total transmission as the gas sample. Radiation is absorbed in the gas cell only at those specific spectral line wavelengths which are characteristic of that gas species; in the neutral absorber radiation is absorbed equally at all wavelengths.

The difference in the source energy removed by the gas and the neutral absorber is the desired pollutant concentration signal. If the correlation coefficient between the spectra of the standard and the unknown is zero (random spectral line overlap) the same total energy will be removed from the beam by the neutral and the gaseous absorbers and no net signal results. If the correlation coefficient between the

spectra is plus unity (exact spectral line overlap) a signal will result. Little change will be observed in the source energy when transmitted through the gas cell because the exact wavelengths at which energy is selectively attenuated by the gas cell have already been attenuated by the pollutant, but the neutral absorber will attenuate the source energy non-selectively, resulting in a difference signal proportional only to the specific pollutant's absorption. This signal is related by calibration to the average concentration of the specific pollutant over the path between the source and receiver.

7.3.10.2 System Description

A passive, down-looking system uses the naturally occurring infrared radiation of the ground or other terrain as the source of radiant energy. The receiver/detector is mounted in an aircraft and examines the source radiation after its absorption by the intervening atmosphere.

The integrated vertical column concentration of the pollutant species is measured instead of the horizontal concentration as did the previously described long-path bistatic systems.

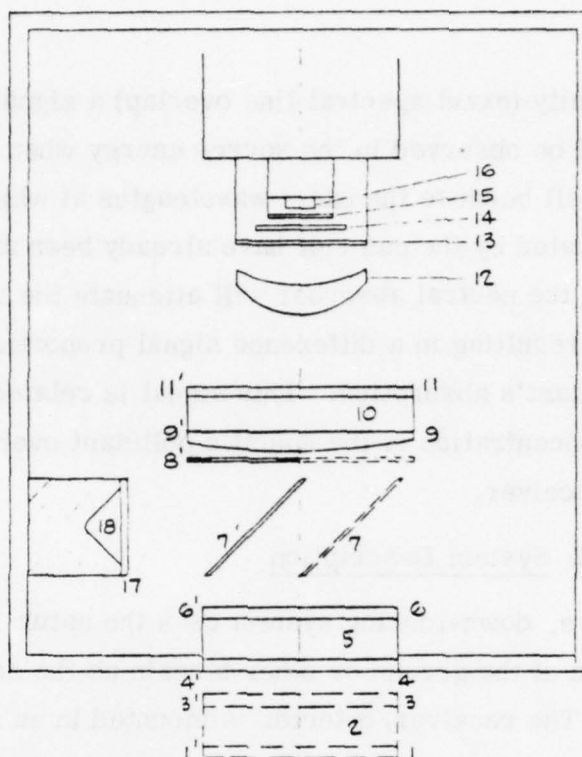
Such a system can quickly provide pollutant vertical column concentrations over a large grid defined by the aircraft flight pattern.

Schematic and detail drawings of a typical airborne instrument are shown in Figures 7.3.10-1 and 7.3.10-2. Figure 7.3.10-3 is a photograph of this instrument.

7.3.10.3 System Parameters

Source

Because the terrain beneath the airborne instrument is the radiant source it is not under control of the experimenter but varies with the temperature and emissivity existing at the time and location at which data are required.



Legend:

- 1, 1' Front window of external calibration cell
- 2 Gas in external calibration cell
- 3, 3' Rear window of external calibration cell
- 4, 4' Front window of internal calibration cell
- 5 Gas in internal calibration cell
- 6, 6' Rear window of internal calibration cell
- 7, 7' Chopper mirrors
- 8' Aperture
- 9, 9' Lens, serving as front window of gas cell
- 10 Gas in cell
- 11, 11' Rear windows of gas cell
- 12 Field lens
- 13 Window
- 14 Filter
- 15 Window of encapsulated detector
- 16 Detector
- 17 Window in front of calibration blackbody
- 18 Calibration blackbody at temperature T

Figure 7.3.10-1. Schematic of the GFC Instrument.

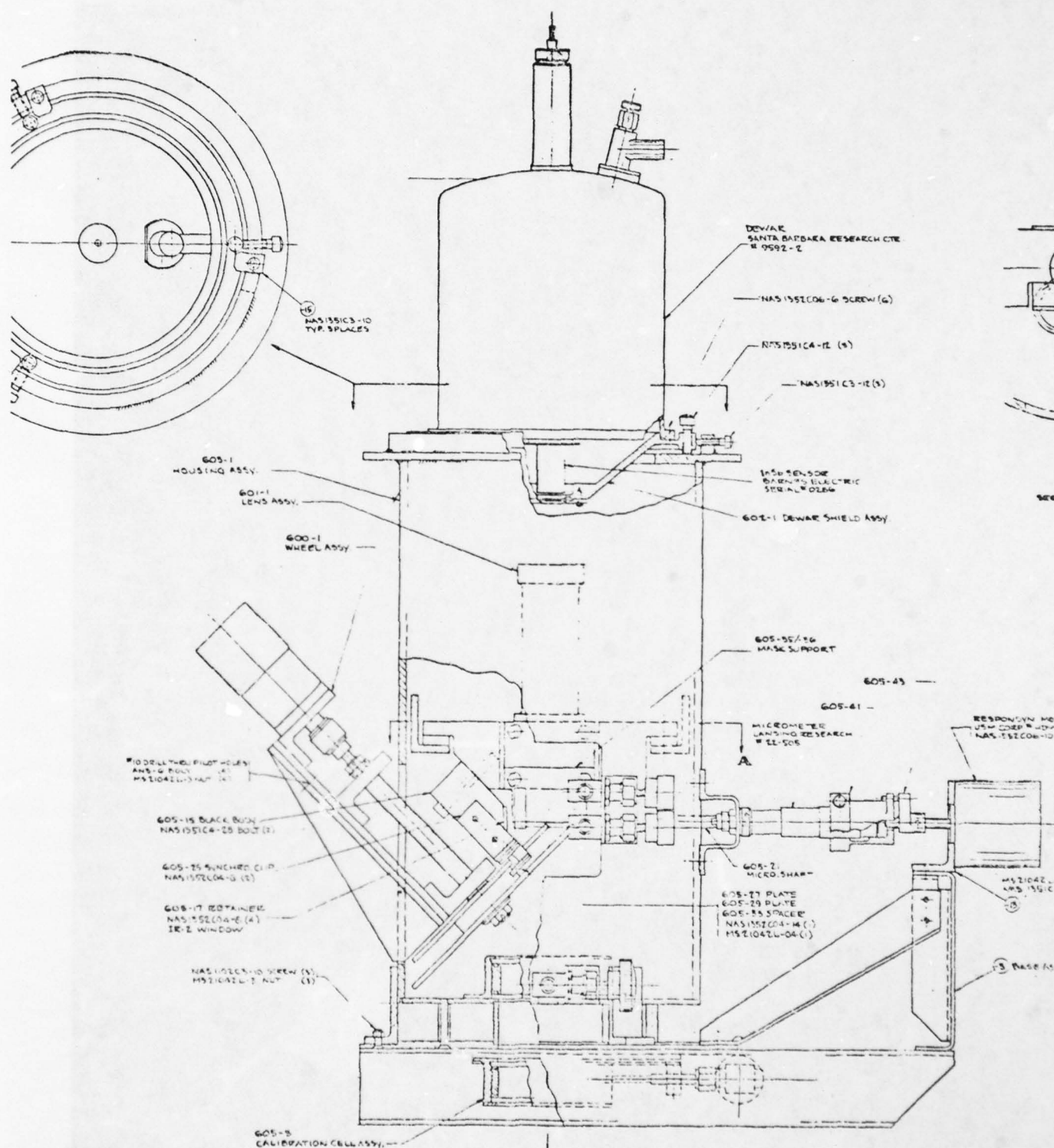


Figure 7.3.10-2. GFC Instrument Assembly.

7.3.10.3d

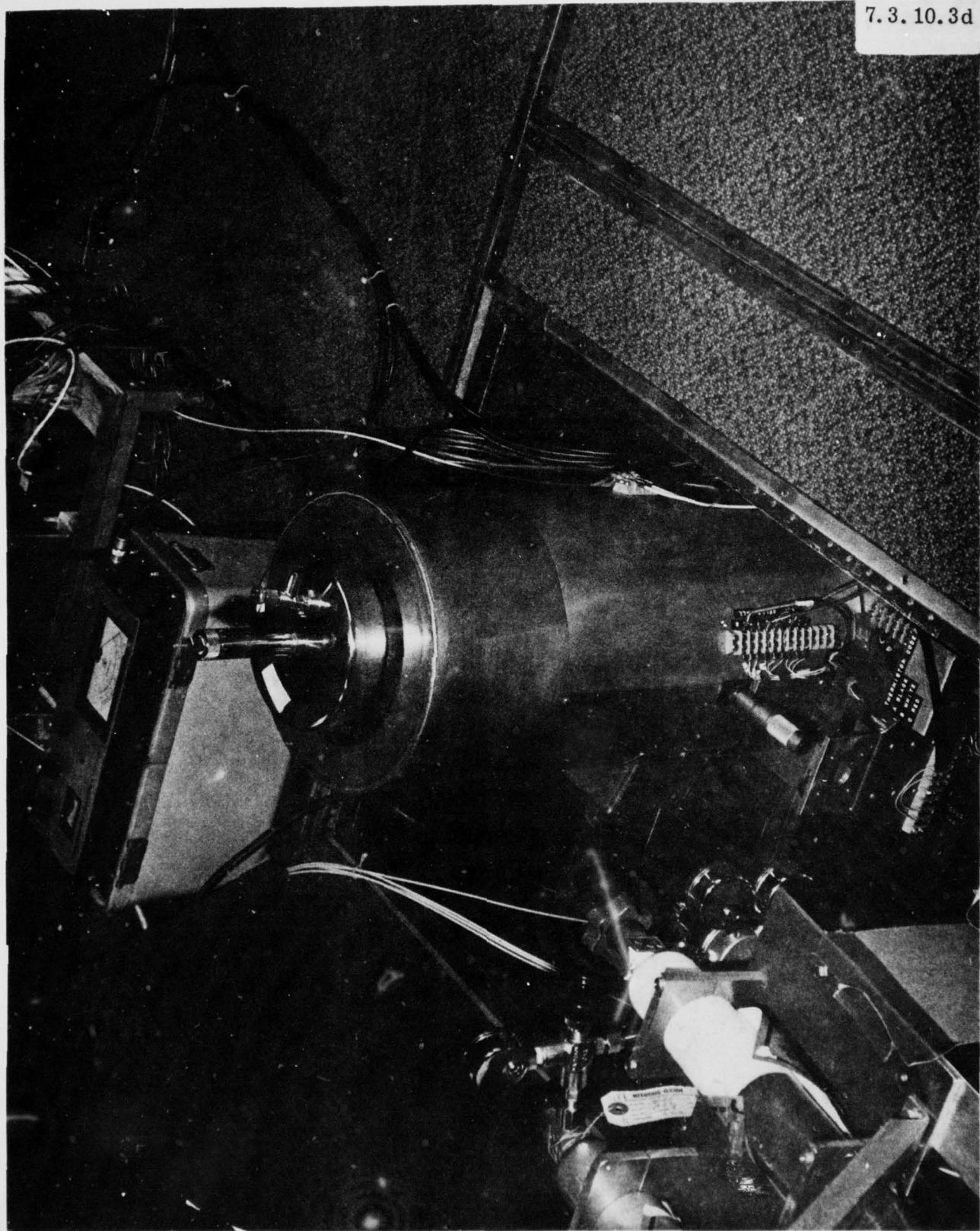


Figure 7.3.10-3. Photograph of GFC Instrument in Aircraft Bay.

Blackbody source spectral radiance curves are shown in Figure 7.3.10-4 for temperatures of 0°C, 20°C and 40°C. However, the actual terrain radiance will be less than this due to the emissivity of the particular surface. Typical values of emissivity are shown below and in Figure 7.3.10-5.

Table 7.3.10-1. Reflectance (ρ) and Emissivity (ϵ) of Common Terrain Features (Ref. 269).

	0.7-1.0 μ	1.8-2.7 μ	3-5 μ	8-13 μ
Green Mountain Laurel	$\rho = 0.44$	$\epsilon = 0.84$	$\epsilon = 0.90$	$\epsilon = 0.92$
Young Willow Leaf (dry, top)	0.46	0.82	0.94	0.96
Holly Leaf (dry, top)	0.44	0.72	0.90	0.90
Holly Leaf (dry, bottom)	0.42	0.64	0.86	0.94
Pressed Dormant Maple Leaf (dry, top)	0.53	0.58	0.87	0.92
Green Leaf Winter Color - Oak Leaf (dry, top)	0.43	0.67	0.90	0.92
Green Coniferous Twigs (Jack Pine)	0.30	0.86	0.96	0.97
Grass - Meadow Fescue (dry)	0.41	0.62	0.82	0.88
Sand - Hainamau Silt Loam - Hawaii	0.15	0.82	0.84	0.94
Sand - Barnes Fine Silt Loam - So. Dakota	0.21	0.58	0.78	0.93
Sand - Gooah Fine Silt Loam - Oregon	0.39	0.54	0.80	0.98
Sand - Vereiniging - Africa	0.43	0.56	0.82	0.94
Sand - Maury Silt Loam - Tennessee	0.43	0.56	0.74	0.95
Sand - Dublin Clay Loam - California	0.42	0.54	0.88	0.97
Sand - Pullman Loam - New Mexico	0.37	0.62	0.78	0.93
Sand - Grady Silt Loam - Georgia	0.11	0.58	0.85	0.94
Sand - Colts Neck Loam - New Jersey	0.28	0.67	0.90	0.94
Sand - Mesita Negra - lower test site	0.38	0.70	0.75	0.92
Bark - Northern Red Oak	0.23	0.78	0.90	0.96
Bark - Northern American Jack Pine	0.18	0.69	0.88	0.97
Bark - Colorado Spruce	0.22	0.75	0.87	0.94

Operational Wavelengths

The operational wavelength and wavelength interval used depends on the specific pollutant gas to be detected. Typical wavelengths are:

CO	4.6 μm
SO ₂	4.0 μm , 8.7 μm
NO	5.3 μm
NO ₂	3.4 μm
Hydrocarbons	3.5 μm

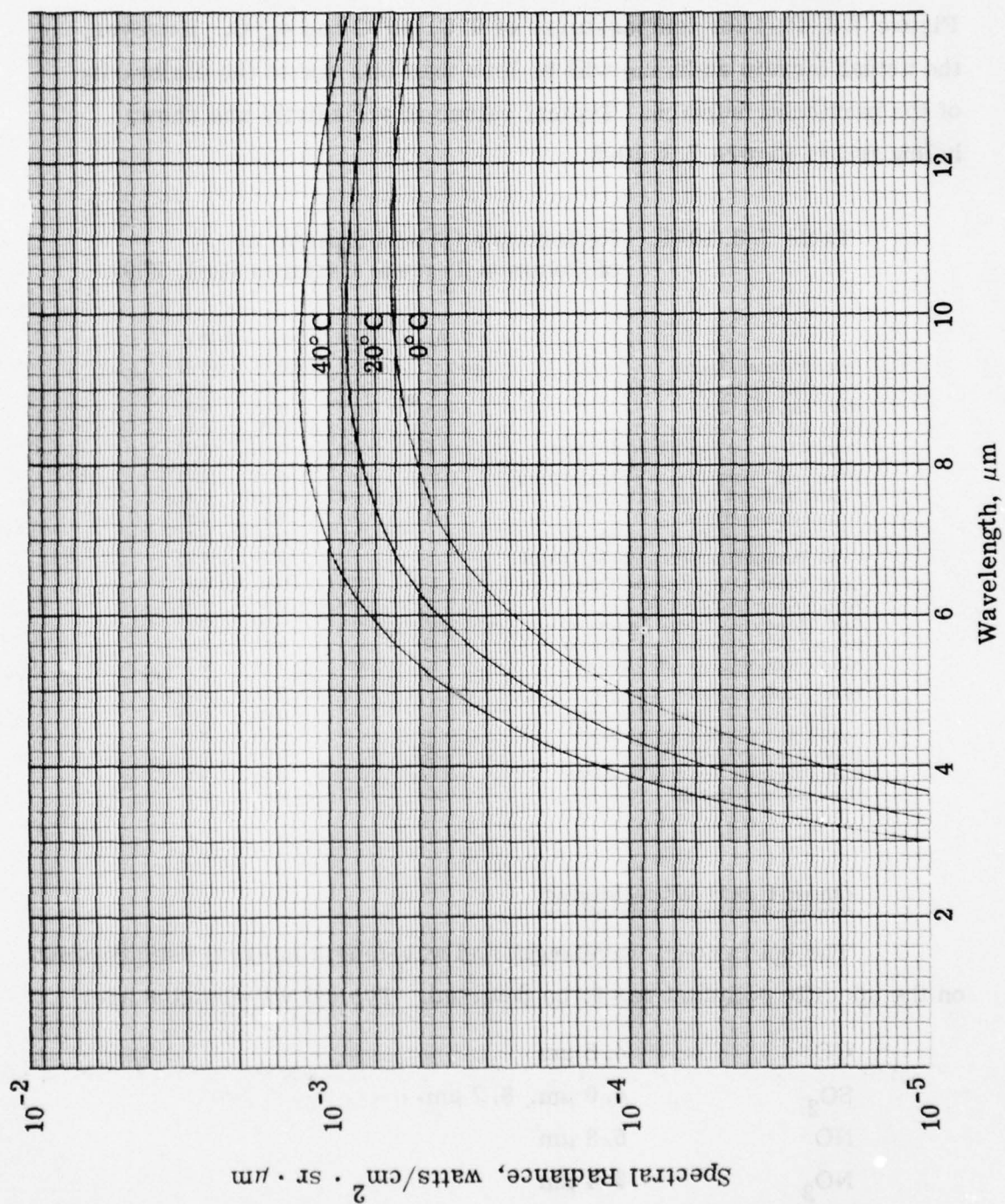


Figure 7.3.10-4. Blackbody Source Spectral Radiance.

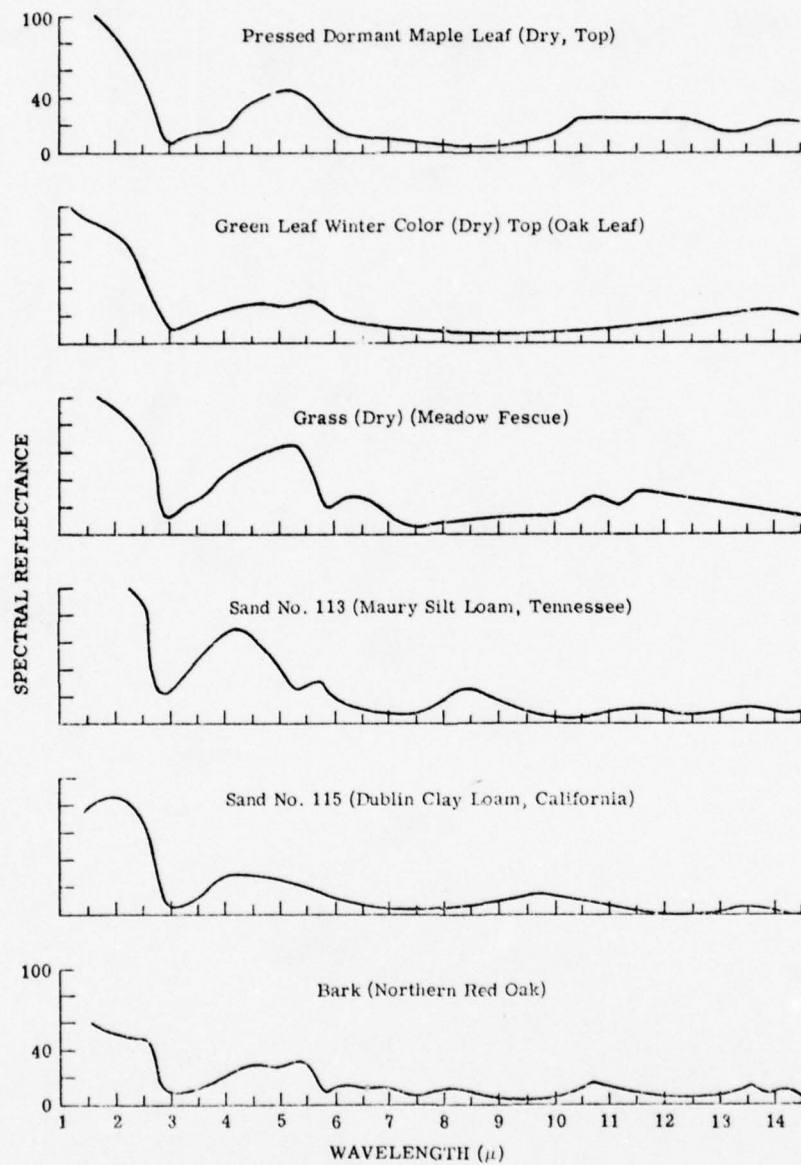


Figure 7.3.10-5. Measured Values of Radiant Emissivity and Reflectance. Emissivity = 1 - Reflectance (Reg. 269).

Wavelengths for other gases are selected on the basis of spectral band parameters and freedom from interfering species, especially water vapor. Not all pollutants are suitable for GFC detection.

Detectors

Some commercially available detectors, their operating temperature and their regions of optimum performance are:

PbS (193K)	2 - 3 μm
PbSe (193K)	2 - 5 μm
InSb (77K)	2 - 5 μm
Pb(Sn, Te) (77K)	5 - 10 μm
Hg(Cd, Te) (77K)	7 - 12 μm

Characteristic values of the parameters D^* for these detectors are shown in Figure 7.3.10-6.

Optics

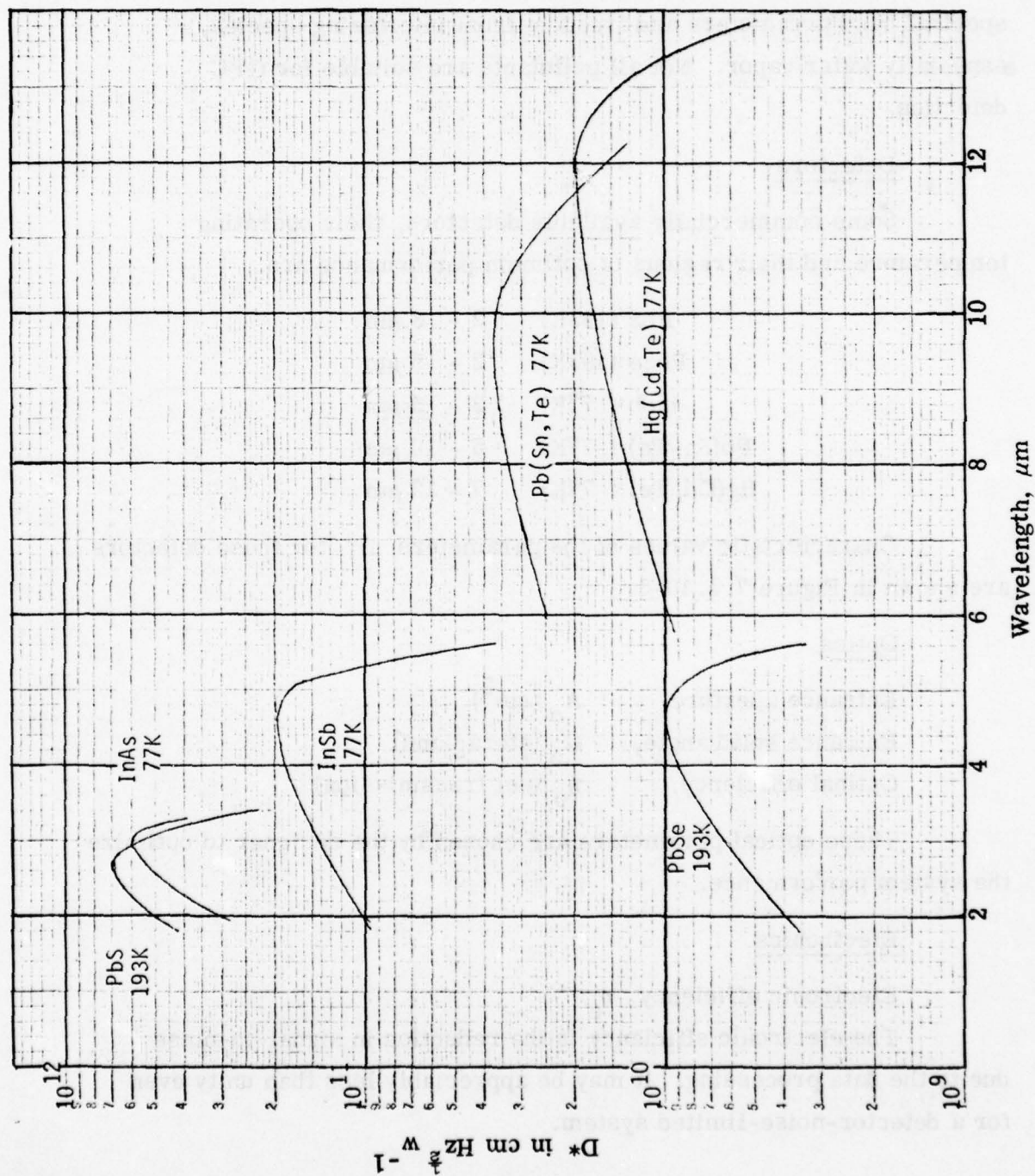
Entrance aperture,	A_o (cm^2)
Entrance solid angle,	Ω_o (steradians)
Optical efficiency,	η_o (net transmission)

These optical parameters are chosen by the designer to optimize the system performance.

Electronics

Electronic efficiency, η_e

The electronic efficiency is the reduction in signal-to-noise due to the data processing. It may be appreciably less than unity even for a detector-noise-limited system.

Figure 7.3.10-6. Specific Detectivity D^* of Typical Detectors.

Electronic bandpass, Δf

Generally $\Delta f = 1/4t$ where t is the 0-63% time constant of the system readout; however, this can vary with electronics design.

7.3.10.4 Theoretical Performance Prediction

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical mode.

From Appendix VII, the signal-to-noise ratio for a gas filter correlation system is:

$$\text{SNR} = P/dP \quad .$$

The numerator, P , contains the source function, the modulation function and instrument optical performance terms. The denominator dP is the instrument performance limitation assuming optimized detector-noise-limited operation.

For an airborne instrument an exact expression for the source function must include contributions from reflected sunlight, terrain emission and atmospheric emission. These are multiplied by the transmission of the atmosphere and are integrated over both altitude and wavelength to determine the exact radiant energy arriving at the instrument.

The following equation illustrates the exact solution for a single wavelength. In use, it must also be integrated with respect to wavelength over the wavelength interval of the instrument.

$$\begin{aligned}
E(\lambda) = & \rho(\lambda) N(T_S, \lambda) \int_{\text{SUN}}^0 \frac{\partial \tau(\lambda, Z)}{\partial Z} dZ \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} dZ \\
& + \epsilon_G(\lambda) N^0(T_G, \lambda) \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} dZ \\
& + \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} N^0[T(Z), \lambda] dZ
\end{aligned}$$

where $\rho(\lambda)$ is the reflectivity of the earth's surface, $\tau'(\lambda)$ is the atmospheric transmission from the sun to the surface, $\tau(\lambda)$ is the atmospheric transmission from the surface to the aircraft at altitude h , T_S is the sun's temperature, $\epsilon_G(\lambda)$ is the surface emissivity, T_G is the surface temperature, $T(Z)$ is the atmospheric temperature at height Z . The transmissivity is given by

$$\tau(\lambda, Z) = \exp \left[- \int_Z^h \sum_i k_i(\lambda, Z') C_i(Z') p_t(Z') dZ' \right]$$

where $k_i(\lambda, Z)$ is the monochromatic absorption coefficient of species i at altitude Z , $C_i(Z)$ is the concentration of species i at altitude Z , and $p_t(Z)$ is the total pressure at altitude Z .

The expressions can be simplified if several reasonable limitations are placed on the measurement parameters.

The first term in the above expression is due to reflected sunlight. This can be neglected if measurements can be constrained to the

longer wavelengths for which the sunlight term is small compared to the terrain radiance. It can be seen from Figure 7.3.10-7 that for $\rho = 0.2$, $\epsilon = 1 - \rho = 0.8$ the sunlight term is down by a factor of 50 or greater at wavelengths longer than $3.6 \mu\text{m}$. Alternately, the flights can be scheduled when the sun is not visible.

If the instrument flight altitude is limited to a value such that the atmosphere can be considered to be single layer having uniform average temperature and pollutant concentration the source expression is further simplified to

$$E(\lambda) = [\epsilon_G(\lambda)N_G^0(T_G, \lambda) - N_{ATM}^0(T_{ATM}, \lambda)]\tau_{ATM}(\lambda) + N_{ATM}^0(T_{ATM}, \lambda) \quad .$$

The last term here is not a function of atmospheric (pollutant) transmission and so creates a spurious output. This spurious output is slightly sensitive to atmospheric temperature and can be removed by zero adjustment of the instrument.

The equation $SNR = P/dP$ can now be expanded:

$$P = [\epsilon_G N_G^0(\lambda, T) - N_{ATM}^0(\lambda, T)] \Delta\lambda A_o \Omega_o \eta_o M$$

$$dP = NEP/\eta_e = (A_d/4t_c)^{\frac{1}{2}}/(\eta_e D^*)$$

and

ϵ_G = Terrain emissivity. See Table 7.3.10-1 and Figure 7.3.10-5.

Units: none

N_G^0, N_{ATM}^0 = Terrain and atmosphere, respectively; black-body spectral radiance. See Figure 7.3.10-4.

Units: $\text{watts/cm}^2 \text{ micron-steradian}$

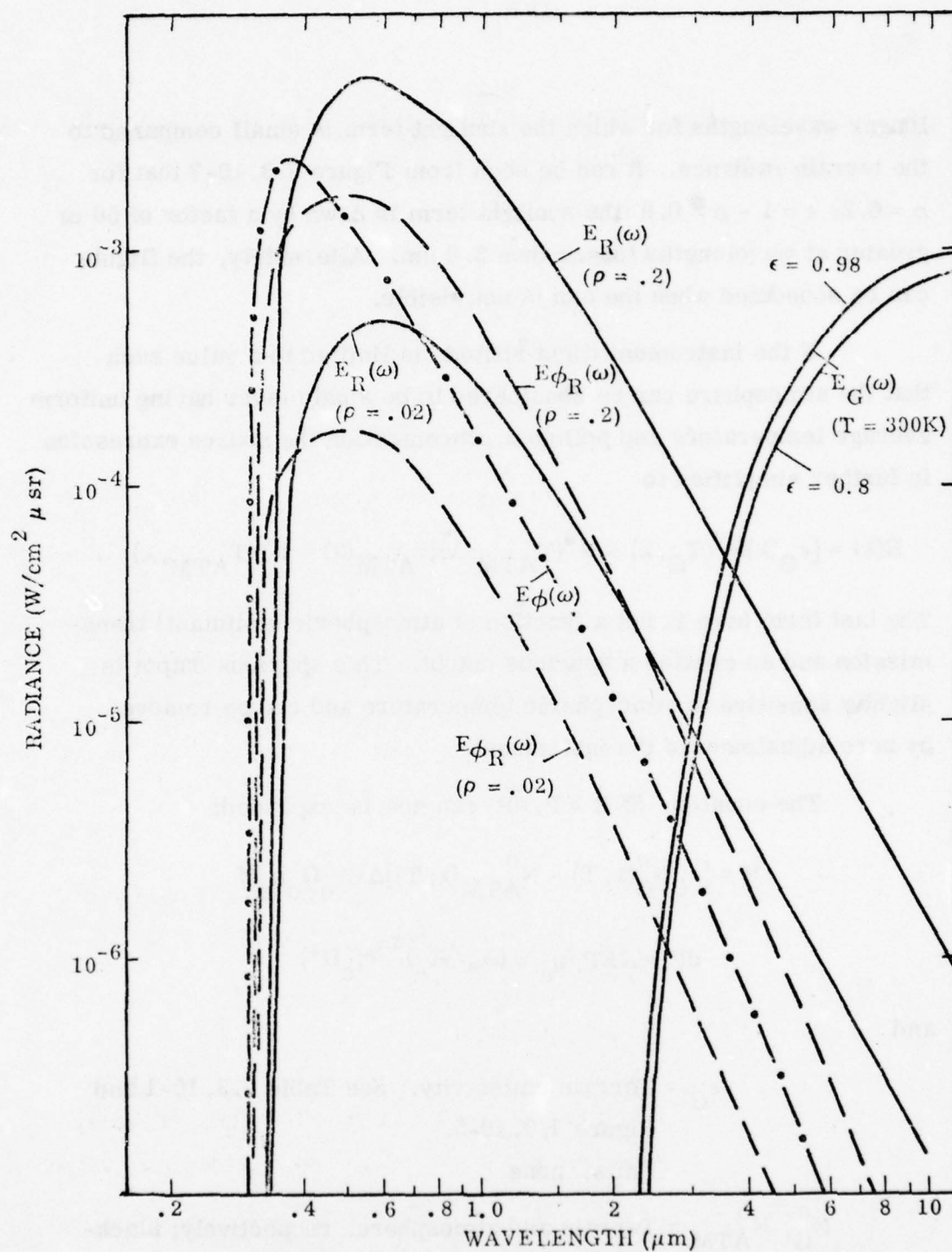


Figure 7.3.10-7. Upwelling Radiation at the Top of the Atmosphere. Contributions from reflected sun radiation $E_R(\omega)$, atmospheric $E_\phi(\omega)$ and $E_{\phi R}(\omega)$, and thermal radiation $E_G(\omega)$. Ground temperature = 300°K, sun zenith angle = 45° (Ref. 270).

$\Delta\lambda$ = Wavelength interval defined by the optical filter.

Units: microns

A_o = Area of entrance optics.

Units: cm^2

Ω_o = Solid angle of field of view.

Units: steradians

A_d = Area of detector.

Units: cm^2

If not known, may be approximated by $1.59 A_o \Omega_o^*$.

η_o = Optical efficiency. Use 0.1* unless otherwise known.

Units: none

t_c = System time constant, 0 - 63% response.

Units: seconds

η_e = Data processing efficiency. Use 0.3* unless otherwise known.

Units: none

D^* = Detector specific detectivity. Use value from Figure 7.3.10-6 unless otherwise known.

Units: $\text{cm Hz}^{\frac{1}{2}}/\text{watt}$

NEP = Noise-equivalent power.

Units: watts

When quoted in system specification, NEP may have units of $\text{watts}/\text{Hz}^{\frac{1}{2}}$; if so, divide given value by $\sqrt{4t_c}$ before using.

*typical values of a well-designed instrument.

M = Modulation factor. Exact calculation requires knowledge of molecular spectral band fine structure parameters. For low concentrations assume:

$$M \approx KcR$$

where K = Empirically determined constant. Unless otherwise known, use 1.0 or $0.1/Rc$; whichever is smaller.

Units: cm^{-1}

c = Fractional concentration of pollutant in atmosphere being monitored, i.e., $\text{ppm} \times 10^{-6}$.

R = Optical path length in atmosphere being monitored.

Units: cm

Calculation Procedure:

Because c (concentration), R (range) and t (time constant) are often field variables, it is convenient to calculate $\text{SNR} = (\text{constant}) \times (cR\sqrt{t})$ so that the comparative effect of these variables on SNR is easily determined.

$$\text{SNR} = G(cR\sqrt{t})$$

where:

$$G = 2(\epsilon_G N_G^0 - N_{\text{ATM}}^0) \Delta\lambda A_o \Omega_o \eta_o \eta_e D^* K / \sqrt{A_d}$$

A_o = Area of entrance optics, cm^2

Ω_o = Solid angle of field of view; approximately $(d/R)^2$,
 where d = width of field of view from R altitude.
 For example, if 50 meter ($= d$) field of view at
 1000 meters ($= R$) altitude, $\Omega_o = 0.0025$ steradians.
 If the field of view is expressed as an angle, B ,
 the formula is $\pi \sin^2(B/2)$; e.g., if $B = 5^\circ$,
 $\Omega_o = 0.006$ steradians.

If actual values are not known for the remaining variables the following values may be assumed:

- ϵ_G : assume Table 7.3.10-1, Figure 7.3.10-5, or 0.8
- N_G^o : assume Figure 7.3.10-4 using $20^\circ C$
- N_{ATM}^o : assume Figure 7.3.10-4 and from $20^\circ C$
 subtract 3° for each 1000 meters flight altitude
- $\Delta\lambda$: assume 0.1
- A_d : assume $1.59 A_o \Omega_o$
- η_o : assume 0.1
- η_e : assume 0.3
- D^* : assume Figure 7.3.10-6
- k : assume 1.0 or $0.1/RC$, whichever is smaller

Known values are always to be preferred over these typical values.

Analytical Determination of SNR

Step 1: Calculate G from above formula using known or assumed parameter values.

Step 2: To calculate SNR given c , R , t :

$$SNR = G c R \sqrt{t}$$

Step 3: To calculate c given SNR, R , τ :

$$c(\text{ppm} \times 10^{-6}) = \text{SNR}/G R\sqrt{t}$$

Graphical Determination of SNR

The formula $\text{SNR} = G(cR\sqrt{t})$ can be written $\text{SNR} = (F)(U)(V)(cR\sqrt{t})$ for which

$$F = (\epsilon_G N_G - N_{\text{ATM}}) \Delta\lambda$$

$$U = (A_o \Omega_o / \sqrt{A_d})$$

$$= 2\eta_o \eta_e D^* K$$

Step 1: Calculate: F

Assume: $\epsilon_G = 1.0$

$$\Delta\lambda = 0.1 \mu\text{m}$$

Flight altitude = 1000 m, 2000 m, 3000 m

Known ground temperature

Known altitude of inversion layer

Known wavelength

Result: Plots in Figures 7.3.10-8a through 7.3.10-8h give F as a function of ground temperature and flight altitude. Do not choose an altitude higher than the inversion layer.

Curve (a)	Wavelength = 3 μm
(b)	Wavelength = 4 μm
(c)	Wavelength = 5 μm
(d)	Wavelength = 6 μm
(e)	Wavelength = 7 μm
(f)	Wavelength = 8 μm
(g)	Wavelength = 9 μm
(h)	Wavelength = 10 μm

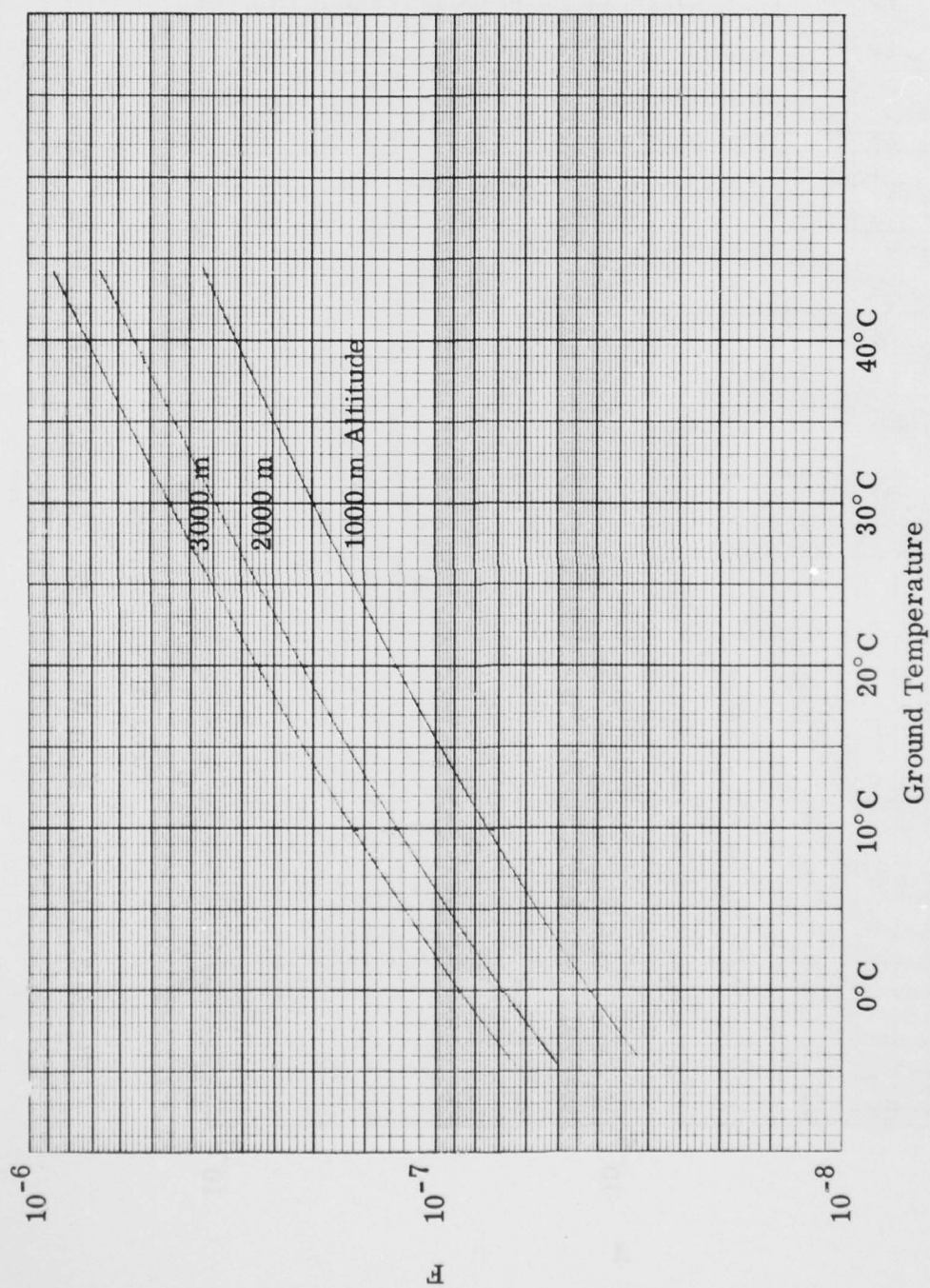
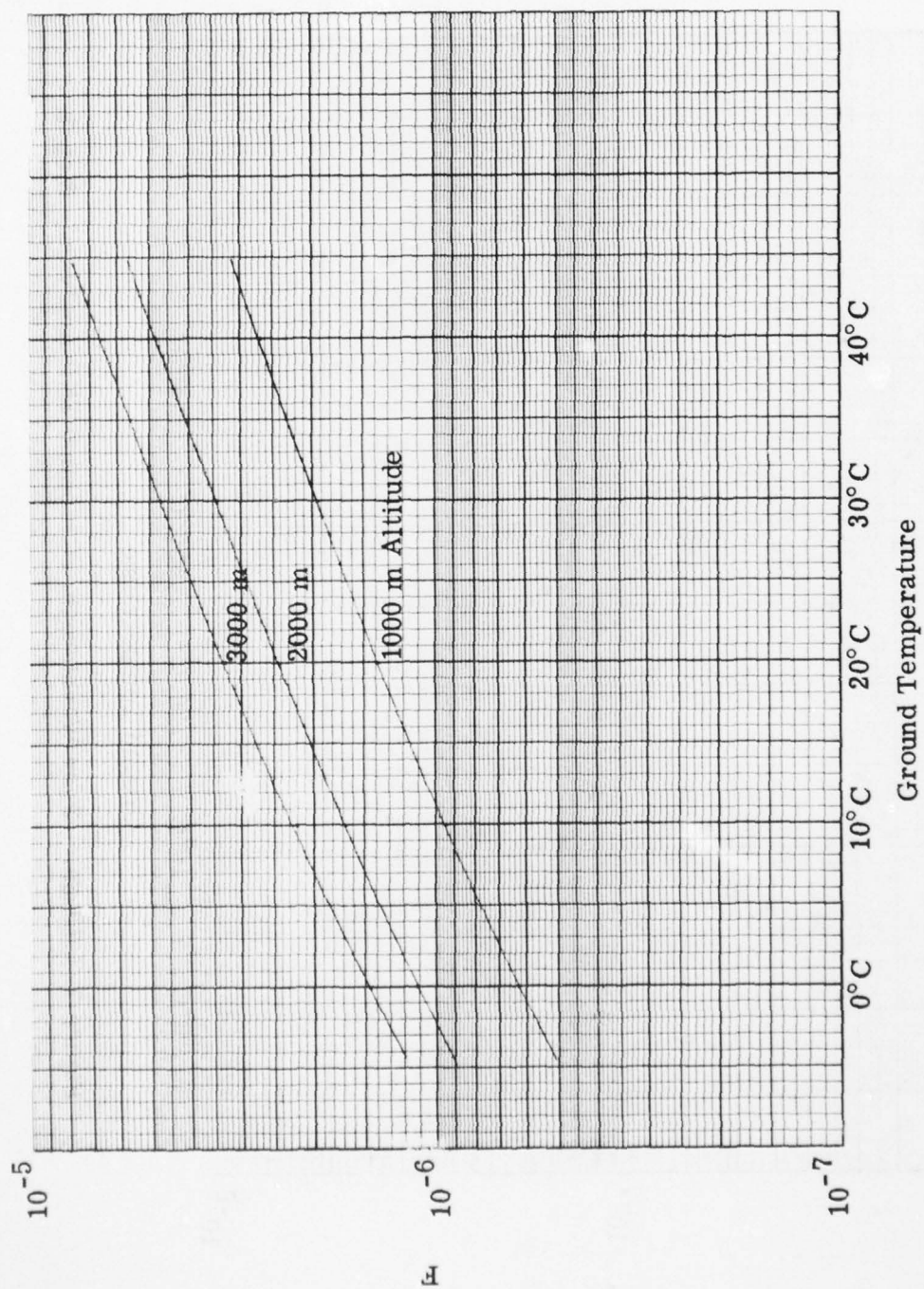


Figure 7.3. 10-8a. $3 \mu\text{m}$ Wavelength. Graphical SNR Analysis - Step 1.

Figure 3.7.10-8b. $4\text{ }\mu\text{m}$ Wavelength. Graphical SNR Analysis - Step 1.

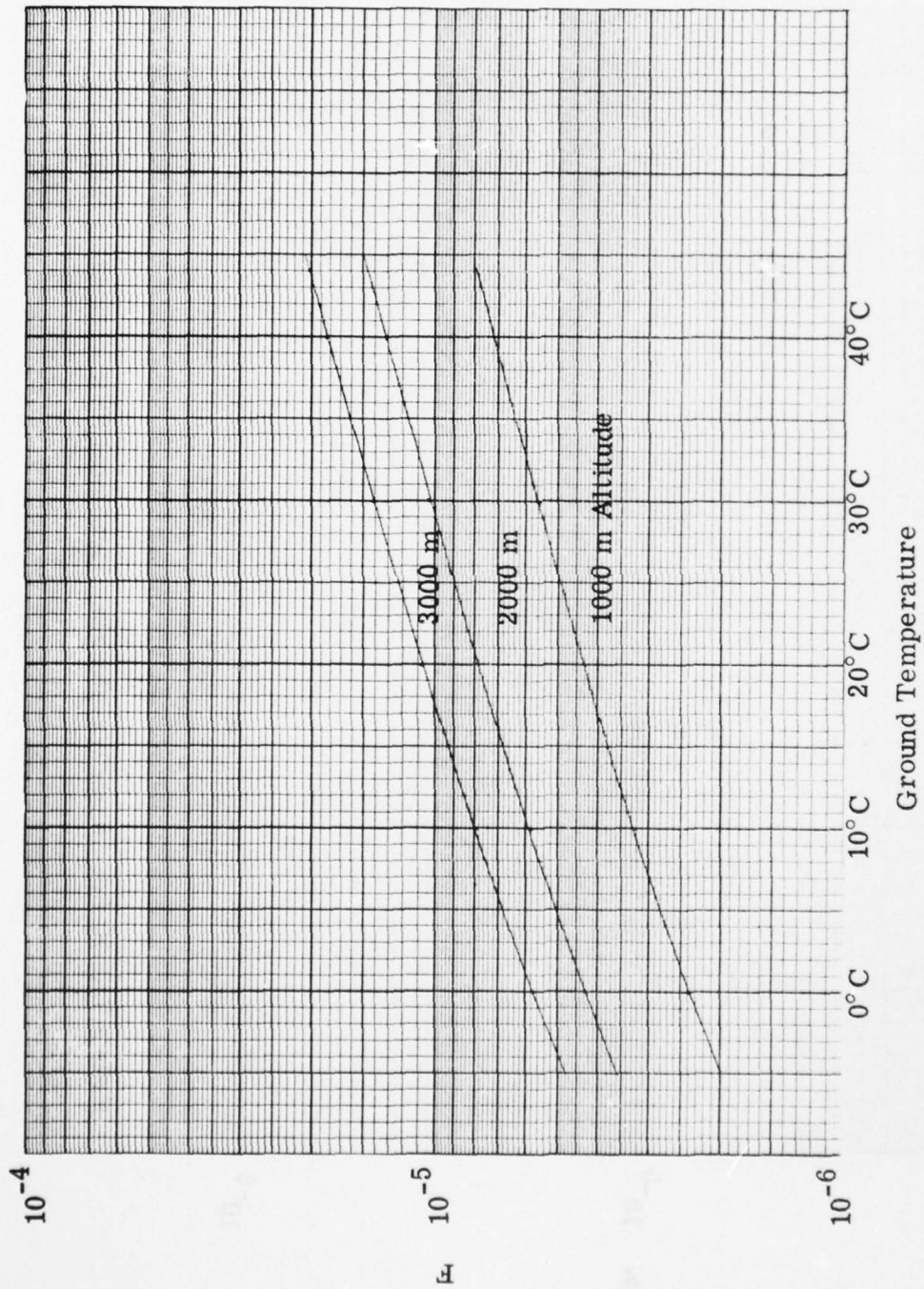
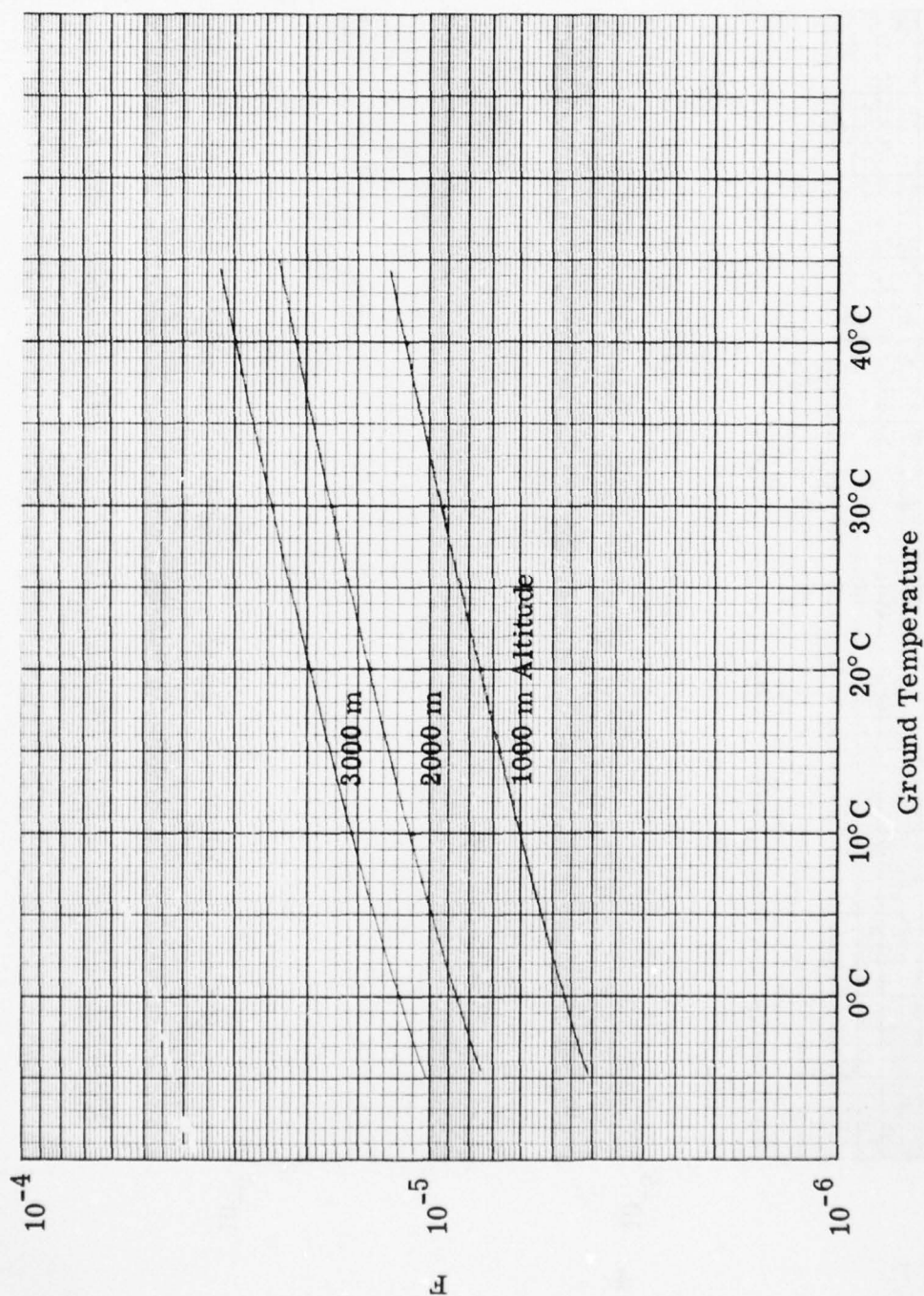


Figure 7.3.10-8c. 5 μm Wavelength. Graphical SNR Analysis - Step 1.

Figure 7.3.10-8d. 6 μ m Wavelength. Graphical SNR Analysis - Step 1.

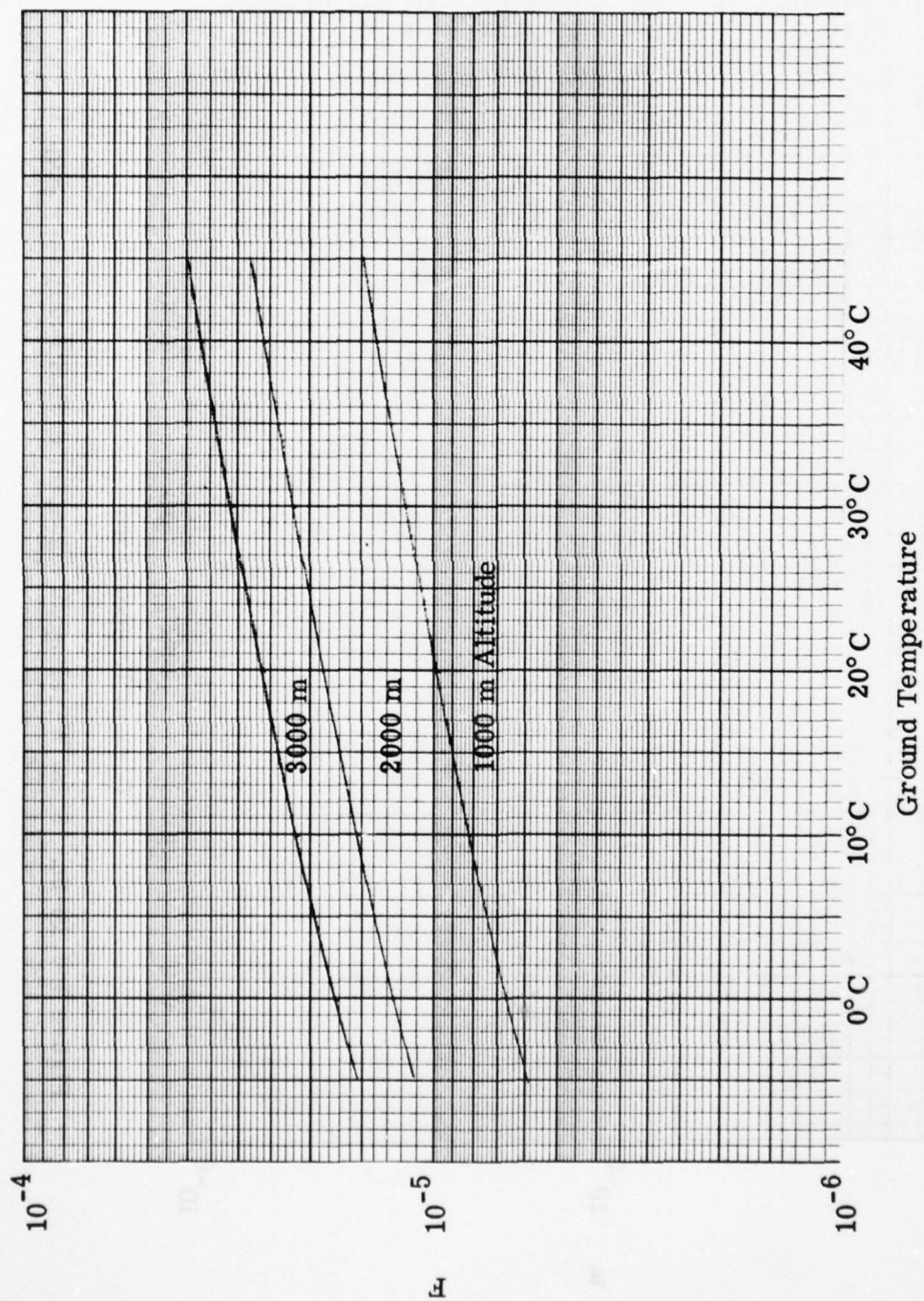
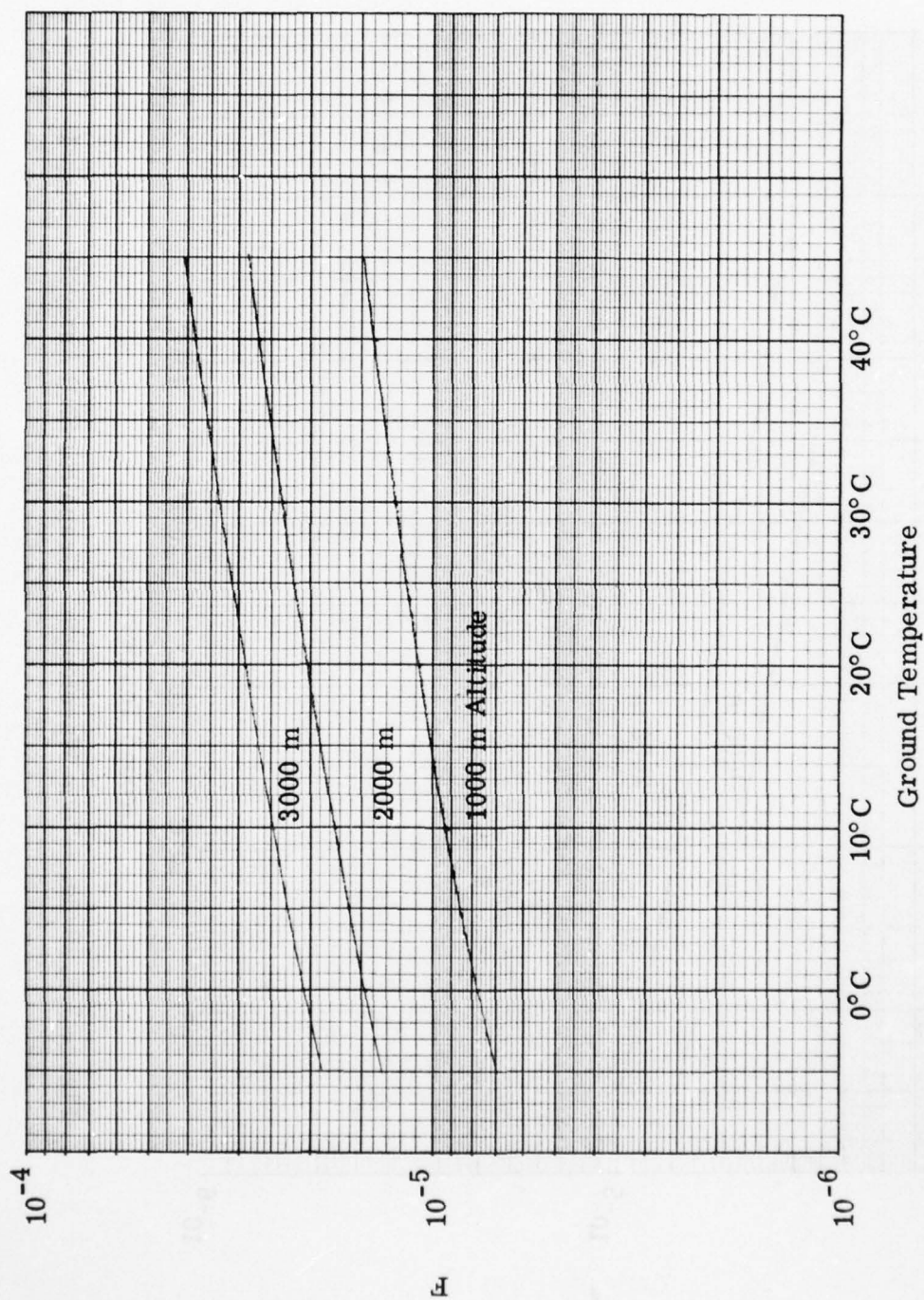
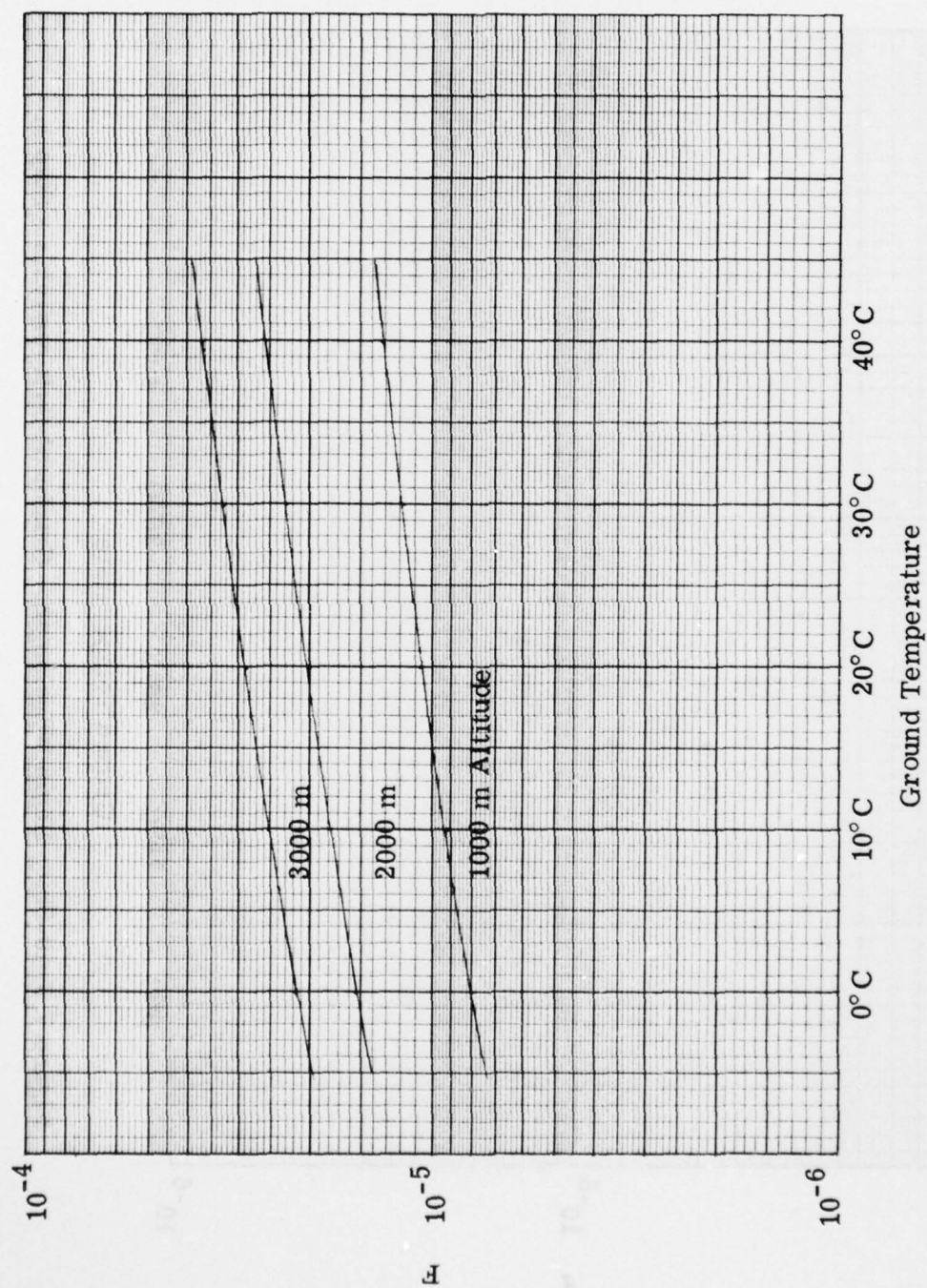


Figure 7.3.10-8e. 7 μ m Wavelength. Graphical SNR Analysis - Step 1.

Figure 7.3.10-8f. 8 μin Wavelength. Graphical SNR Analysis - Step 1.

Figure 7.3.10-8g. 9 μ m Wavelength. Graphical SNR Analysis - Step 1.

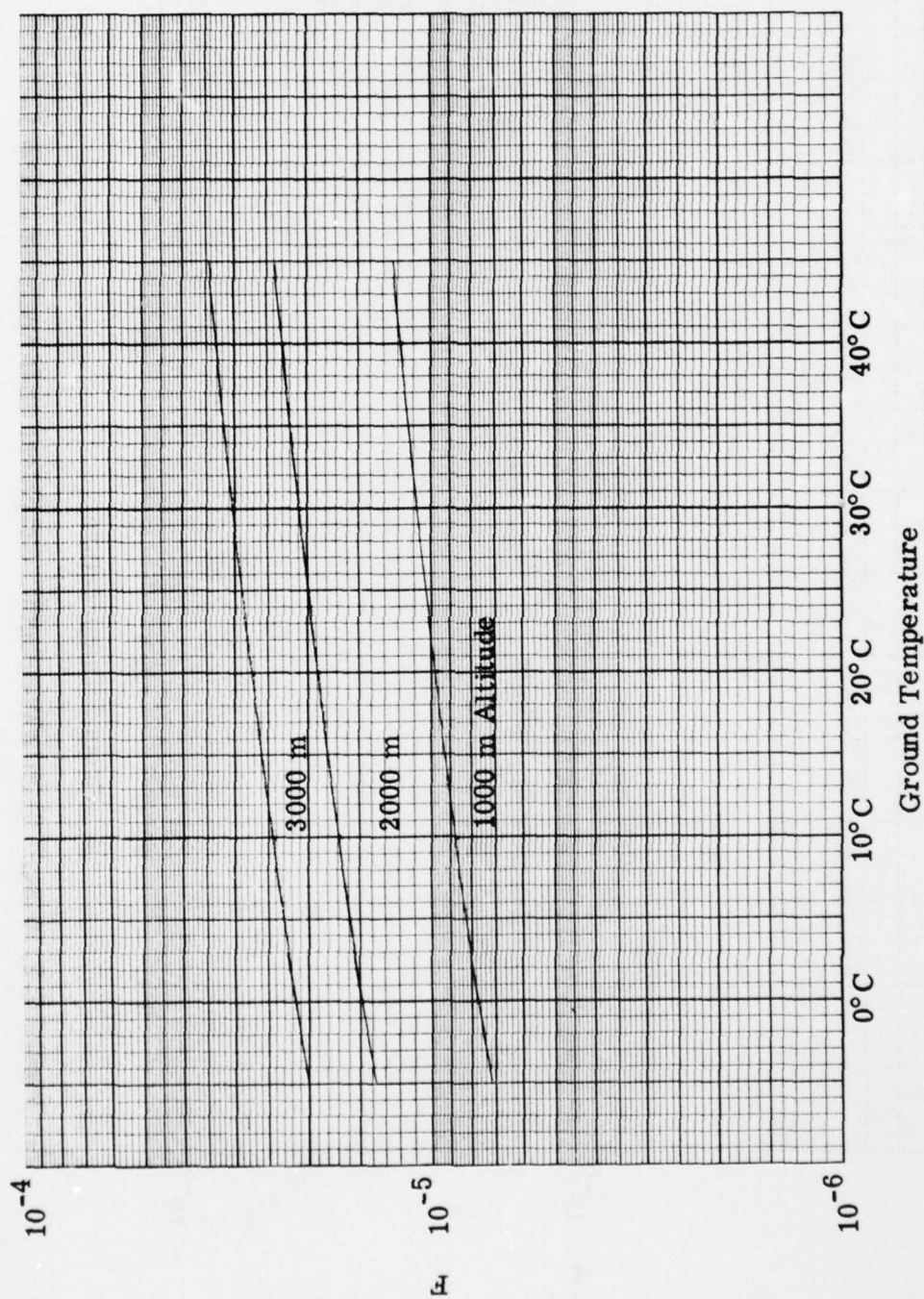


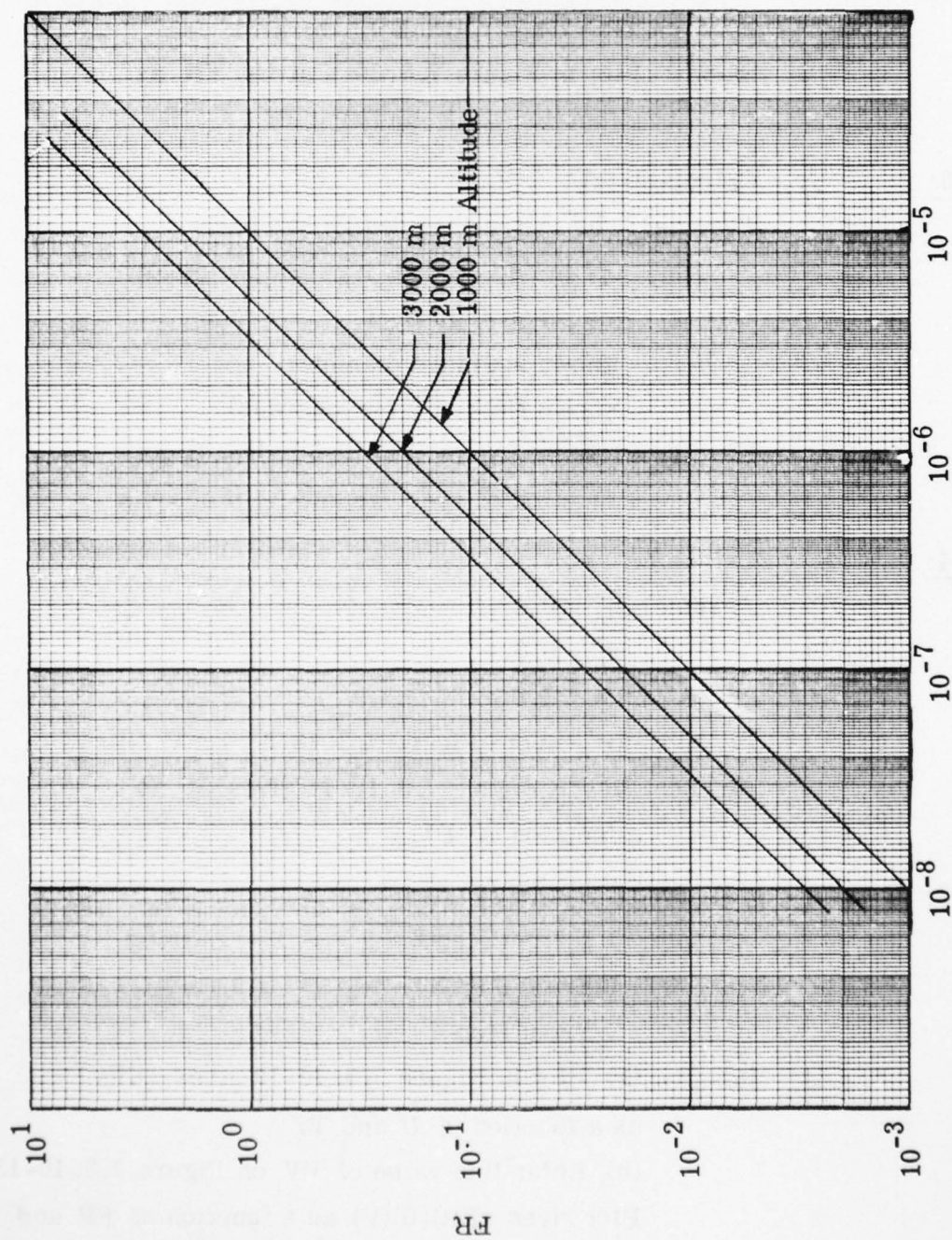
Figure 7.3.10-8h. 10 μ m Wavelength. Graphical SNR Analysis - Step 1.

Step 2:Calculate: $(F)(R)$ Assume: Value of F from Figure 7.3.10-8 R = flight altitude (meters)Result: Plot in Figure 7.3.10-9 gives FR as
a function of F and altitude.Step 3:Calculate: U Assume: The instrument design has been
optimized so that A_d can be approxi-
mated as $1.59 A_o \Omega_o$.

Known aperture diameter

Known field of view (degrees)

Result: Plots in Figure 7.3.10-10 give U as
a function of aperture and field of view.Step 4:Calculate: V Assume: $\eta_o = 0.1$ $\eta_e = 0.3$ $K = 1.0$ D^* = from Figure 7.3.10-6Result: Plot in Figure 7.3.10-11 gives V as
a function of D^* .Step 5:Calculate: $(FR)(U)(V)$ Assume: FR from Step 2 U from Step 3 V from Step 4Result: (a) Plot in Figure 7.3.10-12 gives $(U)(V)$
as a function of U and V .
(b) Enter this value of UV on Figure 7.3.10-13.
Plot gives $(FR)(U)(V)$ as a function of FR and UV .
Values of $FRUV$ greater than 10^9 should not be
considered useful due to interference from other
species.



F (from Figure 7.3.10-8)

Figure 7.3.10-9. Graphical SNR Analysis - Step 2.

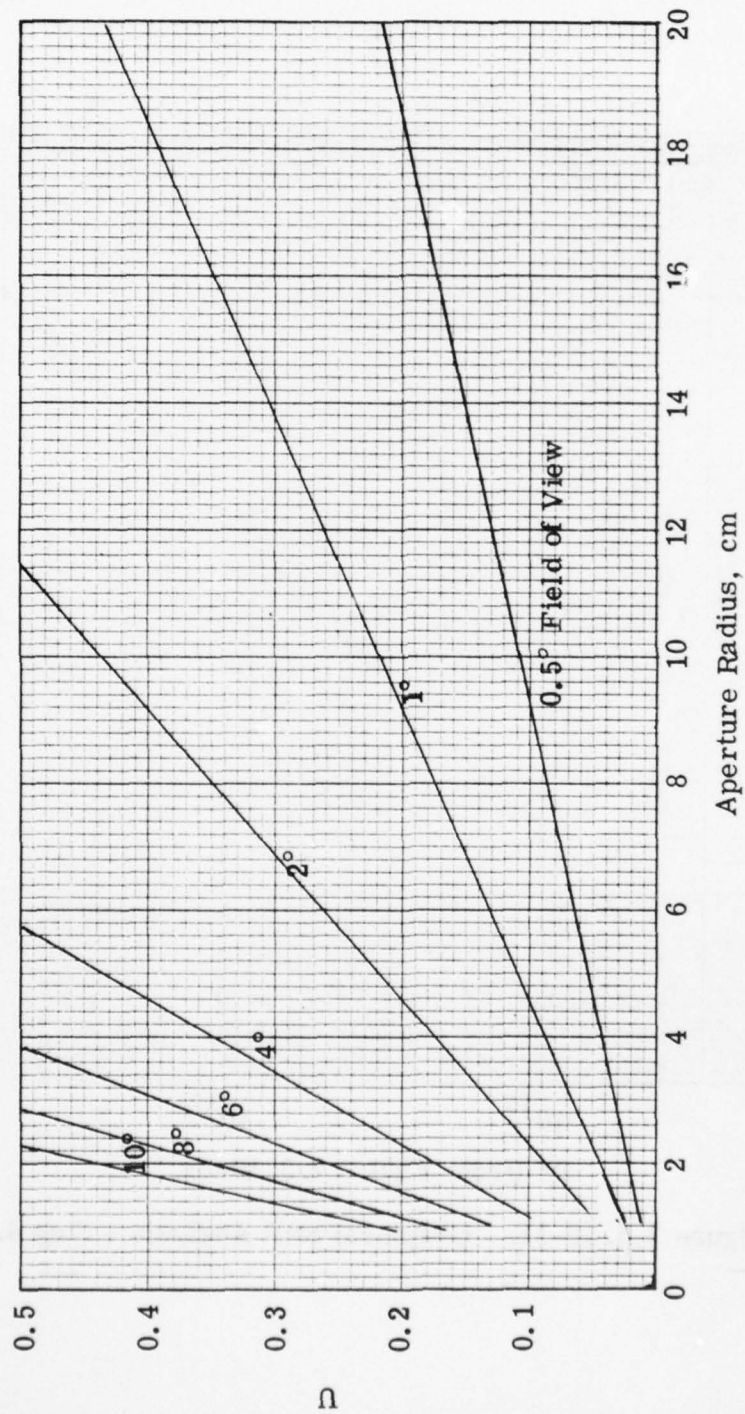


Figure 7.3.10-10. Graphical SNR Analysis - Step 3.

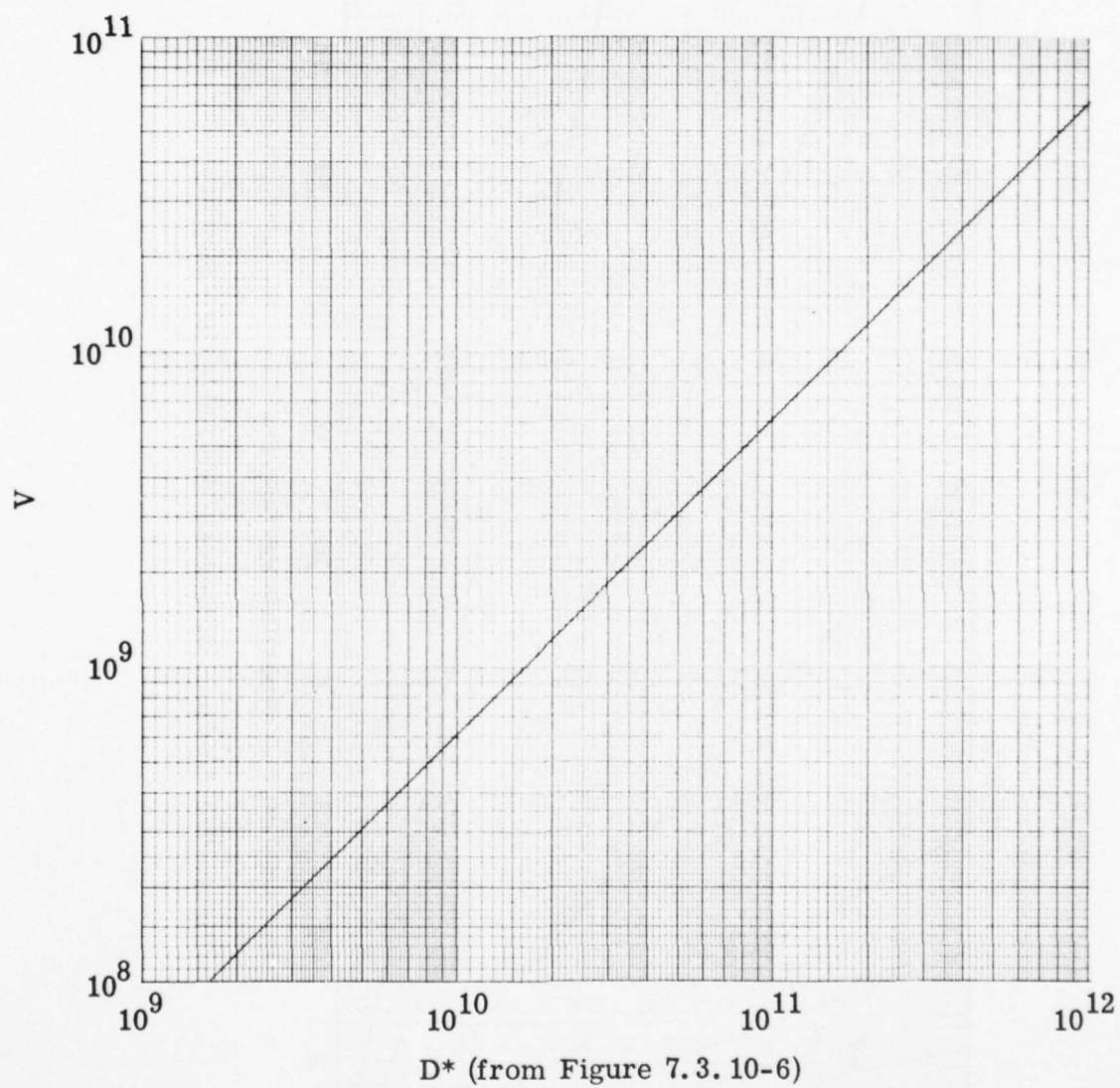


Figure 7.3.10-11. Graphical SNR Analysis - Step 4.

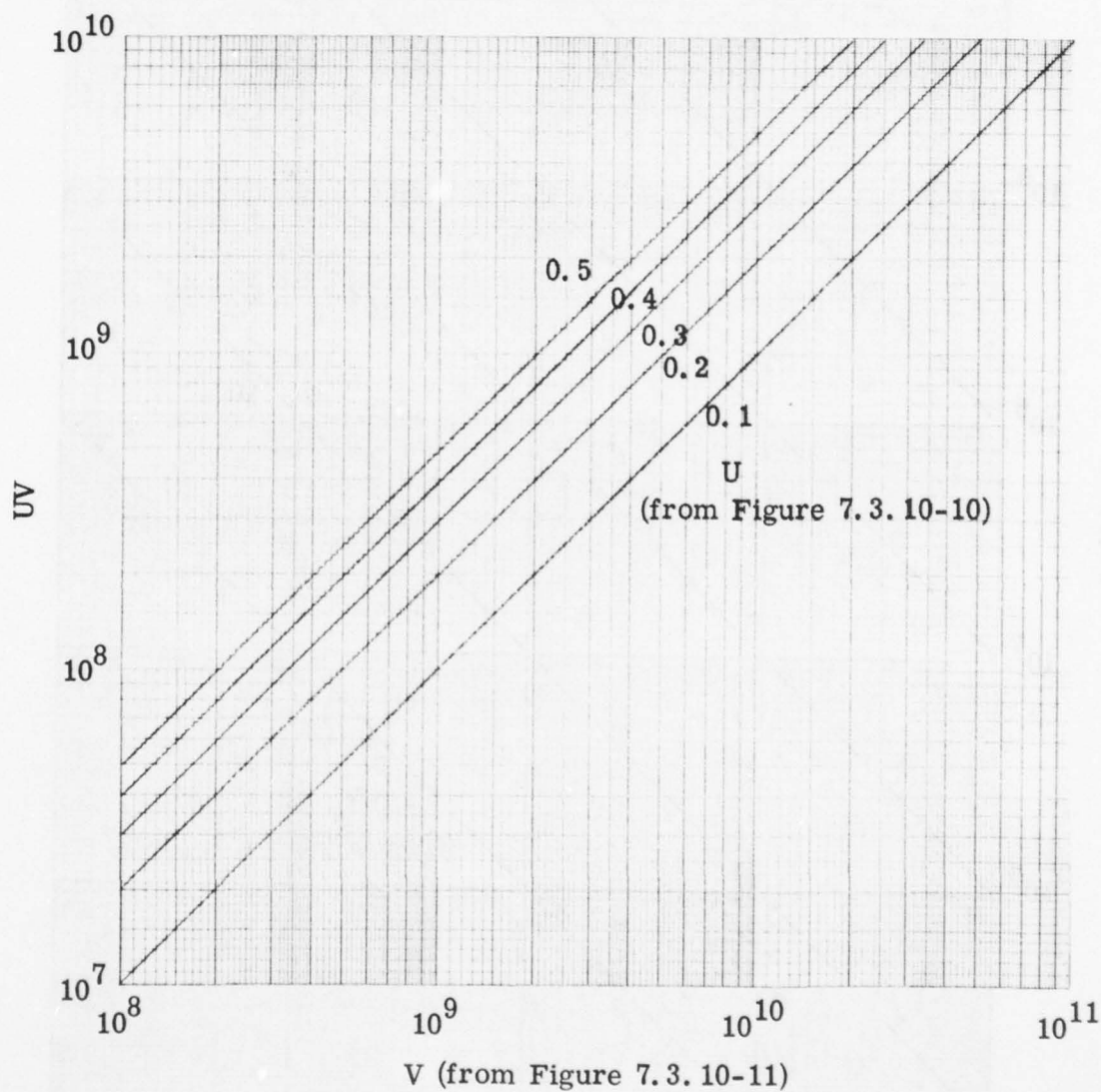


Figure 7.3.10-12. Graphical SNR Analysis - Step 5a.

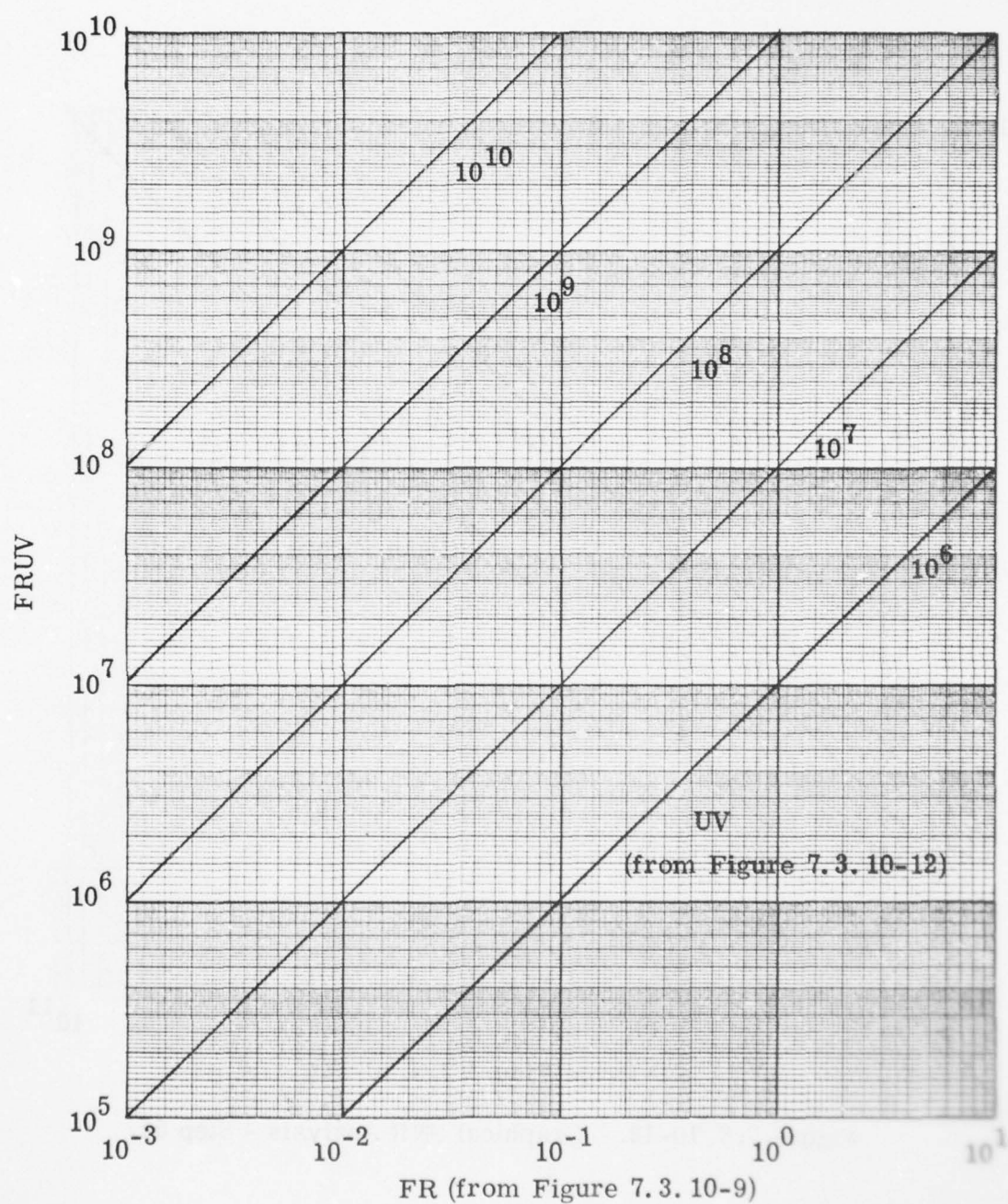


Figure 7.3.10-13. Graphical SNR Analysis - Step 5b.

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DEVELOPMENT OF CRITERIA FOR MONITORING OF AIRPORT GROUND POLLUT--ETC(U)

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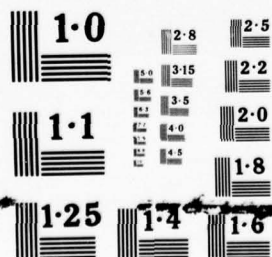
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- Step 6: Calculate: $(FRUV)\sqrt{t}$
Assume: t (time constant) known
($FRUV$) from Step 5
Result: Plot in Figure 7.3.10-14 gives $(FRUV)\sqrt{t}$
as a function of $FRUV$ and the time constant.
- Step 7: Calculate: $SNR = (FRUV\sqrt{t})c$
Assume: $FRUV\sqrt{t}$ from Step 6
Various values of time constant
Result: Plots in Figure 7.3.10-15 give resulting
signal-to-noise ratio for various values of
pollutant concentration.

7.3.10.5 Special Performance Requirements

The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

In addition, the user should be cautioned about proceeding when low signal-to-noise ratios are expected, as peak random noise is typically a factor of five higher than the rms value commonly quoted.

7.3.10.6 Data Analysis Procedure

Analysis is usually performed by comparing the experimental data with an empirically determined calibration curve; theoretical calibration requires computer analysis of the molecular spectral band fine structure parameters.

A calibration curve is obtained experimentally by inserting a calibration cell into the optical path (see Figure 7.3.10-1) using a blackbody background and charging the cell with known concentrations of the pollutant gas. The temperatures of the gas (representing the atmosphere) and the blackbody background (representing the earth) are recorded and converted to units of radiance.

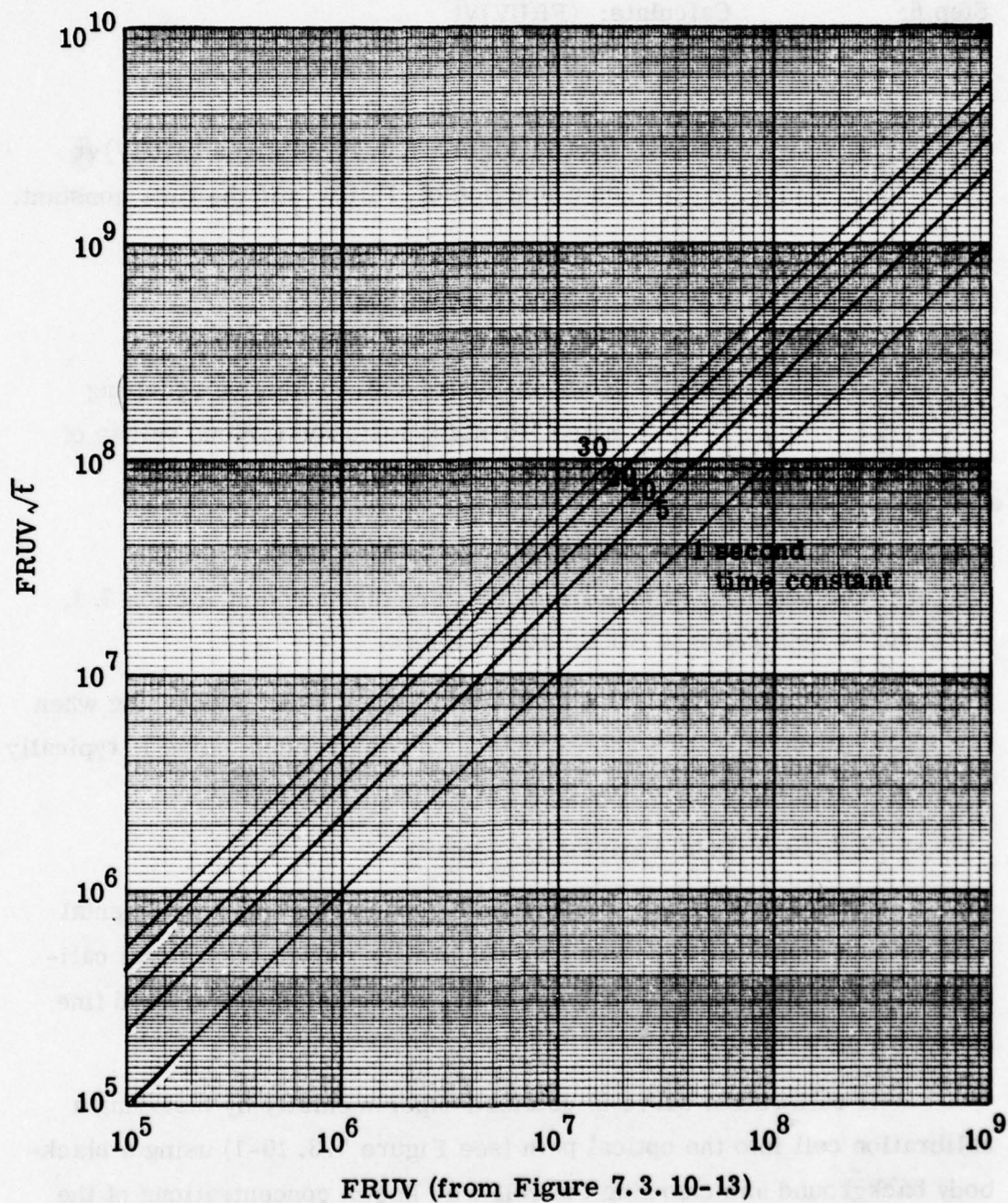
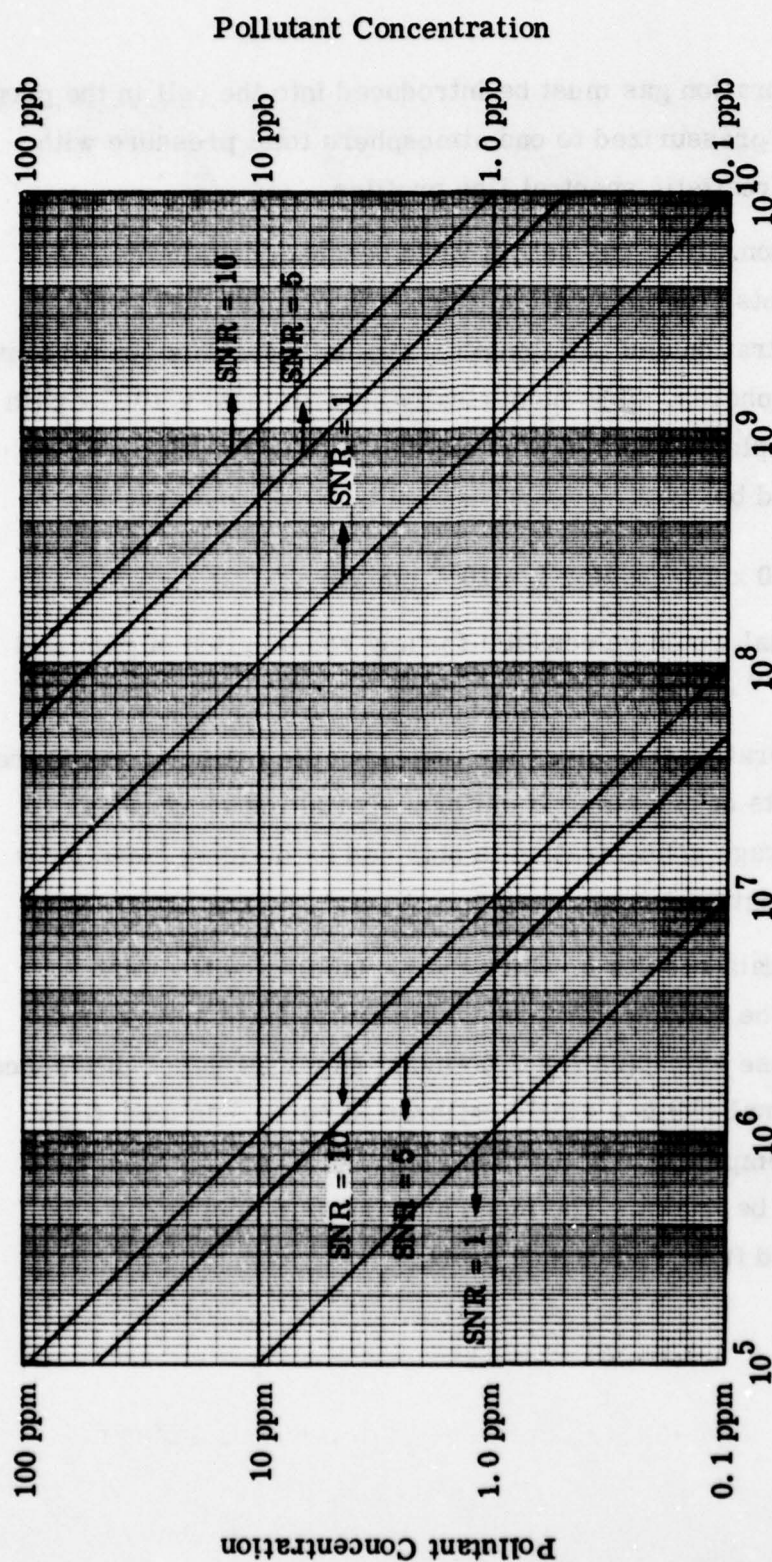


Figure 7.3.10-14. Graphical SNR Analysis - Step 6.



FRUV√t (from Figure 7.3.10-14)

Figure 7.3.10-15. Graphical SNR Analysis - Step 7.

The calibration gas must be introduced into the cell in the proper concentration and pressurized to one atmosphere total pressure with nitrogen to cause realistic spectral line profiles.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to $\text{ppm} \times 10^{-6} \times \text{path length}$. For example, 10 ppm in a 50 cm cell through which the beam passes twice would be

$$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm}$$

The resulting signal would be constant for any combination of ppm and range equaling 10^{-3} cm atm.

The calibration thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.

A set of data results in which the variables are the total pollutant gas and the radiance difference the atmosphere and ground. The product of these variables (total pollutant gas \times radiance difference) plotted against signal yields a single calibration curve. In use, flight altitude, ground temperature and emissivity, and mean atmospheric temperature must be known. The mean atmospheric temperature is preferably obtained from radiosonde probe.

7.4 Remote Monitors Providing Line Integral Data

In Section 6.2.2.2, Selection and Ranking, none of the Line Integral Monitors was judged sufficiently developed to be ranked acceptable at this time for Air Enforcement Monitoring. However, the two uplooking monitors presented here, especially the one using a gas filter correlation receiver, are very promising for future selection. An uplooking monitor, mounted in a truck or van driven around the airport boundary will measure the vertical burden in a closed loop. From the data together with wind velocity and path geometry, the pollutant mass emission rate may be determined for the entire airport as a source.

Note: Since these monitors are developmental, the Performance Predictions and Data Analysis Procedures are necessarily brief and are not presented in the detail provided for previous instruments.

7.4.1 Infrared Spectrometer (Tunable Receiver) Uplooking Monitor

7.4.1.1 Principle of Operation

An upward looking spectrometer may be used as a passive device to measure the vertical burden (ppm-m) of a pollutant in the infrared, ($4 - 10 \mu\text{m}$), if its sensitivity and spectral resolution is sufficient to "isolate" the spectral radiance emitted by the pollutant from that emitted by other atmospheric species. Any pollutants in this spectral region for which sensitivity and resolution requirements are met may be monitored; which meet these criteria are not yet determined. The radiance is measured at two adjacent wavelengths, one for the pollutant emission, and one for the clean atmosphere emission. The difference of these radiances, together with knowledge of the atmospheric temperature, is used to estimate the vertical burden of the pollutant.

7. 4. 1. 2 System Description

The system consists typically of a collecting telescope, a spectrometer, including a moveable grating to vary the wavelength of the radiation leaving the exit slit, and a detector system. A calibration source may be built into the spectrometer, or it may be externally viewed by the telescope. A schematic of a scanning spectrometer system is shown in Figure 7. 4. 1-1.

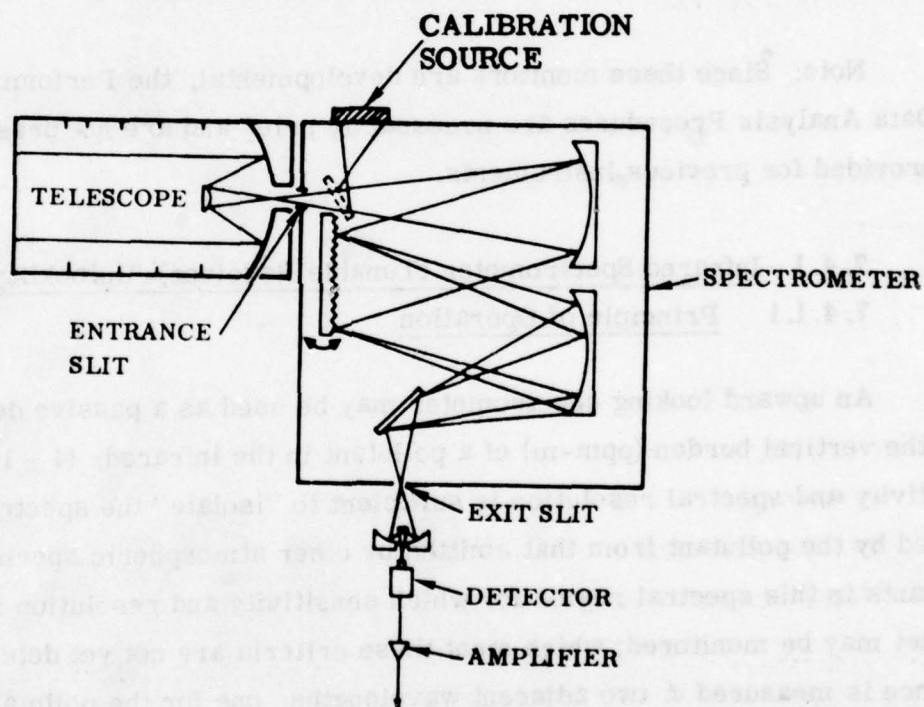


Figure 7. 4. 1-1. Schematic of a Scanning Spectrometer

7. 4. 1. 3 System Parameters**Availability**

No tunable receivers appear to be currently used in the passive upward mode, although General Dynamics Convair⁽²⁷¹⁾ developed a scanning spectrometer system some years ago.

Operational Wavelength Region

Window regions in 4 - 10 μm .

Detector

Commercially available detectors with highest D^* at 77K are 4 μm Indium Antimonide, 77K, $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2} \text{ w}^{-1}$, size 0.1 to 3 mm diameter.

10 μm Lead Tin Telluride, 77K, $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2} \text{ w}^{-1}$, size 0.05 to 2 mm square.

Optics

Collecting Aperture	A_o
Solid Angle	Ω_o
Optical Efficiency	η
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These parameters are variables which must be chosen to fulfill the operational requirements.

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where t_c is the integration time.

7. 4. 1. 4 Theoretical Performance Prediction

Based on the selected system parameter, the performance can be predicted for a detector-noise-limited system. The signal to noise ratio for the system is given by

$$\begin{aligned} \text{SNR} &= \frac{\eta A_o \Omega_o \Delta\lambda [N_{\lambda_1} - N_{\lambda_2}]}{\sqrt{2} \text{ NEP}} \\ &= \eta \sqrt{\frac{A_o \Omega_o}{2 \Delta f}} \frac{D_{\lambda}^* \Delta\lambda [N_{\lambda_1} - N_{\lambda_2}]}{f/\text{no}} \end{aligned}$$

where $f/\text{no} \approx (\Omega_d)^{-1/2}$, $\Omega_o \approx 0.17 \Delta\lambda/\lambda$ for spectrometers, N_{λ_1} is the radiance at the wavelength where a pollutant line is located and N_{λ_2} is the radiance between absorption lines.

This may be re-written as

$$\text{SNR} = \eta \left(\frac{A_o \Omega_o}{2 \Delta f} \right)^{1/2} \frac{D^* \Delta\lambda \tau_c \epsilon_p N^o(\lambda, T)}{f/\text{no}}$$

where τ_c is transmissivity of "clean" atmosphere, ϵ_p is the emissivity of the pollutant layer, and $N^o(\lambda, T)$ is the atmospheric blackbody radiance.

Thus the SNR of a given instrument depends on the state of the atmosphere, i. e., the amount of water vapor and aerosol (these determine τ_c), and the atmospheric temperature, and the amount of pollutant.

To compute SNR:

Step 1. From instrument parameters calculate the parameter (IP)

$$(IP) = \eta \left(\frac{A_o \Omega_o}{2\Delta f} \right)^{1/2} \frac{D^* \Delta \lambda}{f/no}$$

Typical values might be

$$\eta = 0.01$$

$$A_o = 78.5 \text{ cm}^2$$

$$\Omega_o = 6.8 \times 10^{-5} \text{ sr}$$

$$\Delta f = 4.17 \times 10^{-3} \text{ Hz (60 sec time constant)}$$

$$D^* = 5 \times 10^{10} \text{ W}^{-1} \text{ Hz}^{1/2} \text{ cm}$$

$$\Delta \lambda = 0.005 \text{ } \mu\text{m}$$

$$f/no = 5$$

Hence (IP) = 4.00×10^5 for this example.

Step 2: Determine the atmospheric transmission τ_c . This should be performed by computer program, if available, using known or assumed values of the atmospheric structure parameters. This will probably not be possible, and the typical value

$$\tau_c = 0.9$$

may be assumed.

Step 3: Measure or estimate atmospheric temperature. Determine N^o from Figure 7.4.1-4.

Step 4: Calculate ϵ_p for pollutant thickness (ppm-m). l - physical thickness of pollutant layer.

$$\begin{aligned}\epsilon_p &= 1 - e^{-kC_t l} \\ &= 1 - e^{-k(\text{cm}^{-1}\text{atm}^{-1})C_p l (\text{ppm-m}) \times 10^{-4}}\end{aligned}$$

in which the 10^{-4} factor converts ppm-m to cm-atm. The variation of SNR with ϵ_p as a function of T is given in Figure 7.4.1-2 for two wavelengths. The values of SNR may be scaled for different instrument parameters, and different values of τ_c .

Example: Assume the instrument parameters are as given in Step 1, and the atmospheric conditions give $\tau_c = 0.9$ and $T = 290\text{K}$. Assume $\text{SNR} = 10$ is required for minimum sensitivity, then from Figure 7.4.1-2 we find $\epsilon_p \approx 0.035$ for $10 \mu\text{m}$.

From Step 4:

$$\epsilon_p = 1 - e^{-k(\text{cm}^{-1}\text{atm}^{-1})C_p l (\text{ppm-m}) \times 10^{-4}}$$

Hence, the minimum detectable $C_p l$ in ppm-m may be calculated for a given k , and assuming the mixing thickness l , the mean layer minimum detectable concentration C_p in ppm may be calculated:

$$C_p l = \left(\frac{1}{kl} \right) \ln (1 - \epsilon_p) - \left(\frac{1}{kl} \right) \ln (1 - \epsilon_p)$$

The variation of minimum detectable concentration with the pollutant layer thickness as a function of k , is given in Figure 7.4.1-3 for the two wavelengths.

Because of the complexity of the calculation of the modulation signal, we are restricted here to describing the effects of the instrument parameters on the resulting SNR. Also, we are restricted to the one pollutant for which the calculations have been done (SO_2) and to the atmospheric conditions which were assumed.

For instrument parameters other than those assumed in Step 1, proceed as follows:

Step 5: Calculate the instrument parameter IP using the formula in Step 1 and using actual values instead of assumed values.

Step 6: Calculate

$$k = IP/4.00 \times 10^5$$

Step 7: Recall the preliminary value of SNR obtained in Step 4, multiply this by the value of IP (Step 6). The result is the actual value of SNR.

$$SNR (actual) = (k) SNR (preliminary)$$

Graphical Procedure

A graphical procedure is not presented because the computational variables are limited to the above instrument parameters.

Until further computer calculations are published, the atmospheric and pollutant parameters are limited to those presented in Figures 7.4.1-2 and -3.

The reader is cautioned that this is a preliminary analysis of a developmental instrument.

7.4.1.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. Special requirements applicable to particular pollutants are described in discussions of other monitors in Section 7.

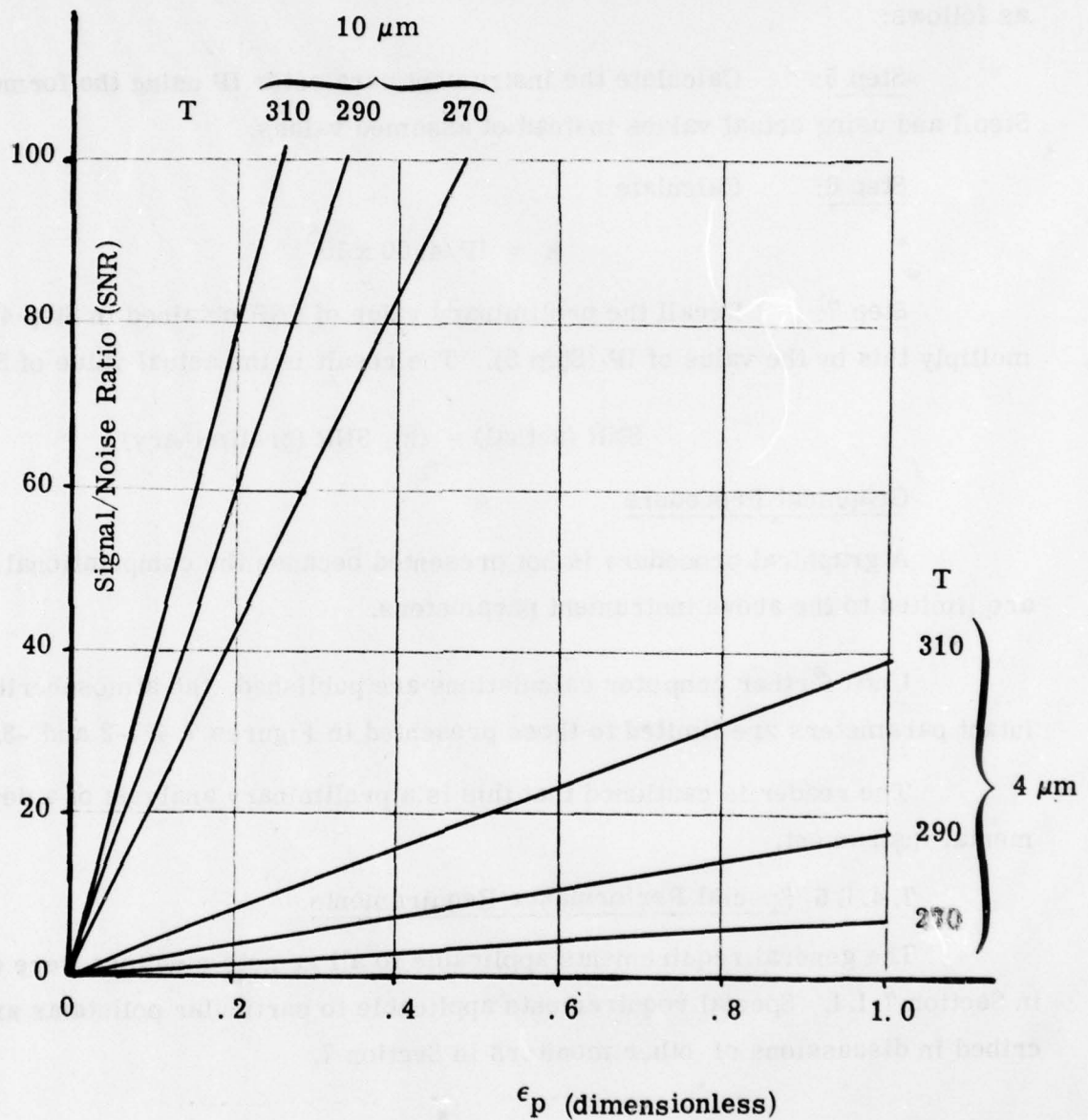


Fig. 7. 4. 1-2

Signal-to-Noise Ratio vs ϵ_p for indicated wavelengths and temperatures and Instrument Parameter $IP = 4 \times 10^5$.

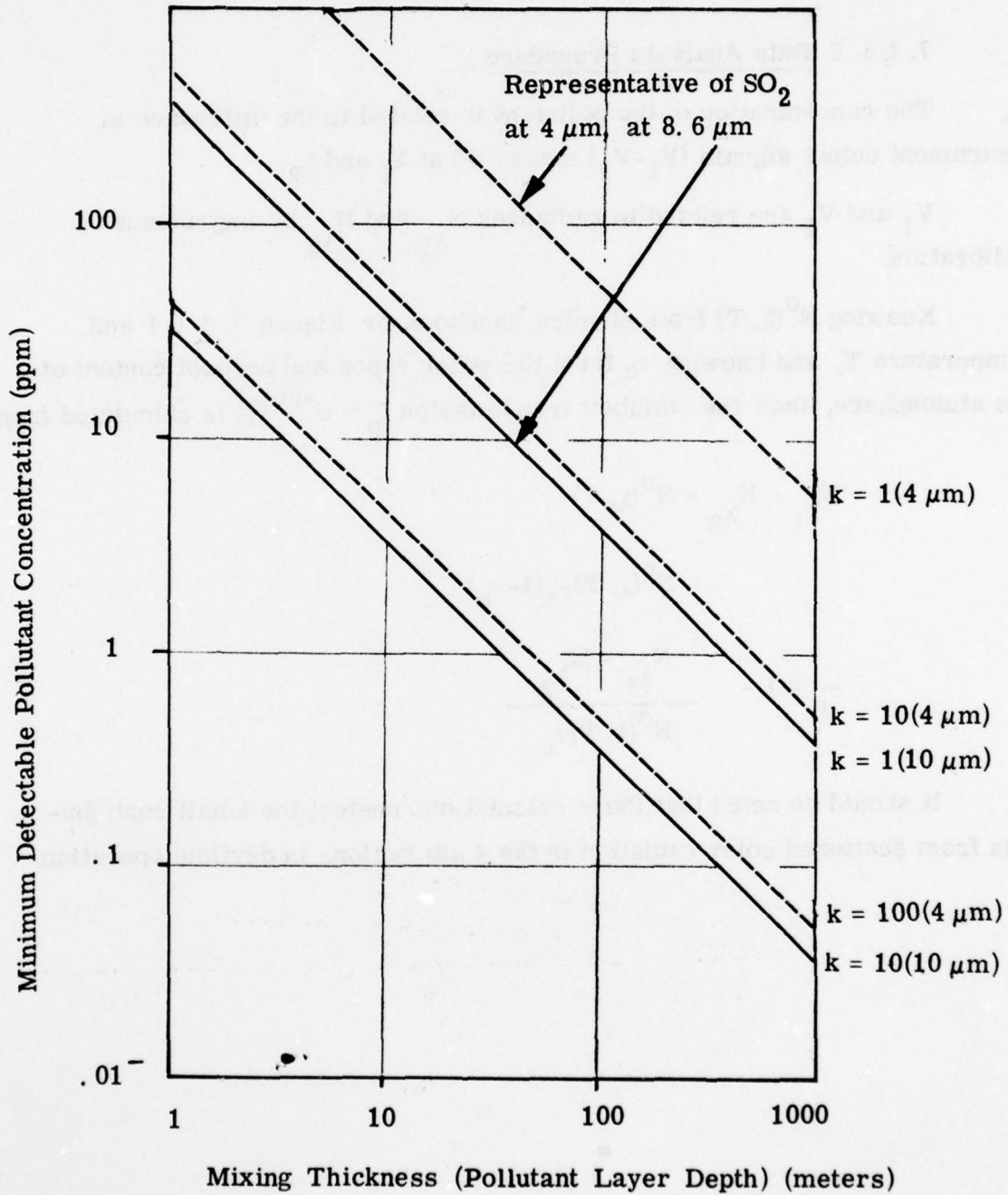


Fig. 7. 4. 1-3. Minimum pollutant concentration (ppm) vs. mixing depth (meters) for various values of k (l/cm)

7. 4. 1. 6 Data Analysis Procedure

The concentration of the pollutant is related to the difference in instrument output signals ($V_1 - V_2$) measured at λ_1 and λ_2 .

V_1 and V_2 are related to radiances N_{λ_1} and N_{λ_2} by instrument calibration.

Knowing $N^0(\lambda, T)$ from physics handbook or Figure 7. 4. 1-4 and temperature T , and knowing τ_c from the water vapor and aerosol content of the atmosphere, then the pollutant transmission $\tau_p = e^{-kCp_t}$ is calculated from:

$$\begin{aligned} N_{\lambda_1} - N_{\lambda_2} &= N^0(\lambda, T) \\ &= N^0(\lambda, T)\tau_c(1 - \tau_p) \\ \tau_p &= 1 - \frac{N_{\lambda_1} - N_{\lambda_2}}{N^0(\lambda, T)\tau_c} \end{aligned}$$

It should be noted that these calculations neglect the small contribution from scattered solar radiation in the $4 \mu\text{m}$ region, in daytime operation.

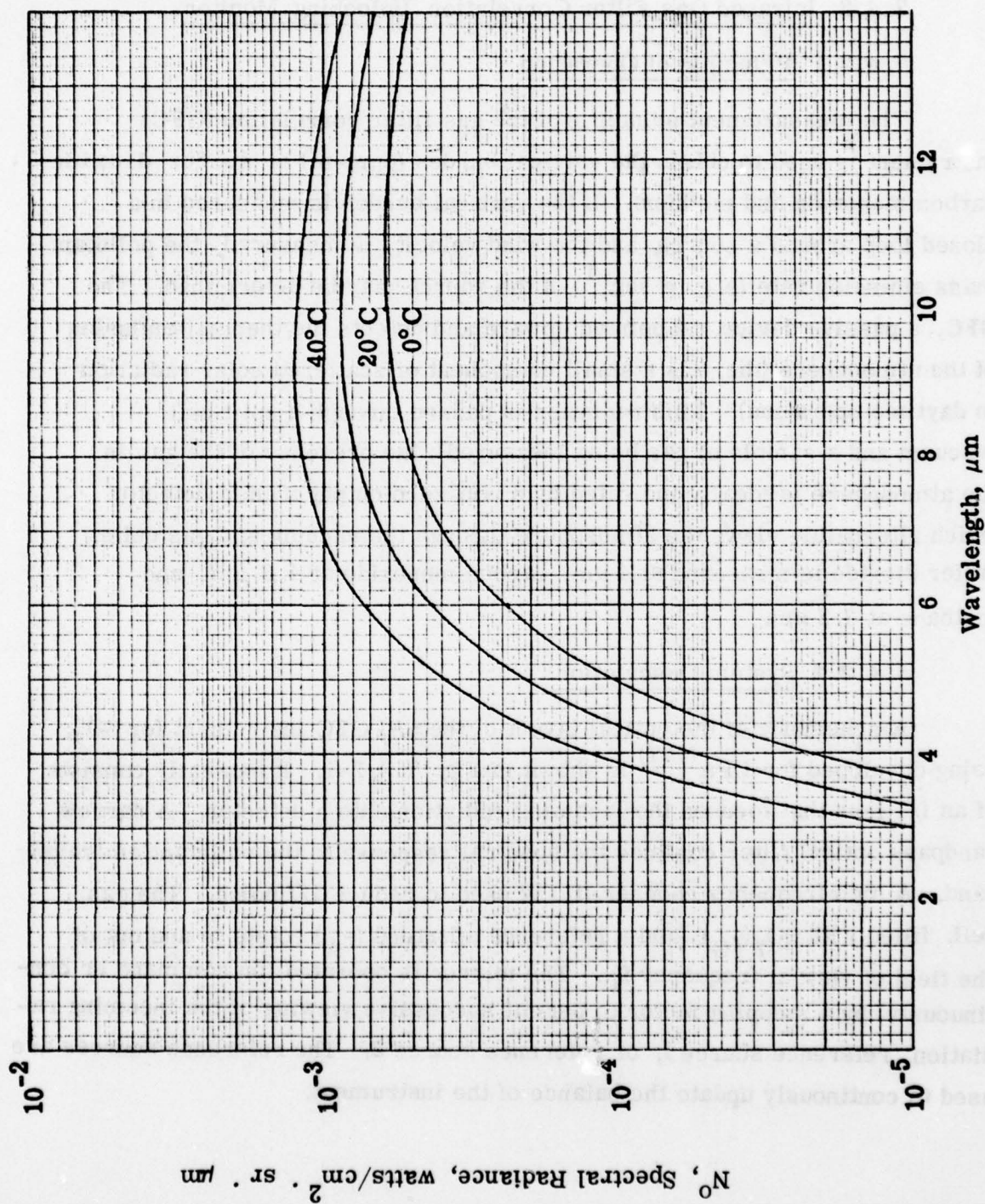


Figure 7. 4. 1-4. Blackbody Source Spectral Radiance.

7. 4. 2 Infrared Gas Filter Correlation Uplooking Monitor

7. 4. 2. 1 Principle of Operation

The measurement principle of the gas filter correlation (GFC) instrument is used to obtain the vertical burden (ppm-m) of sulfur dioxide, carbon monoxide and methane. If the vertical burden is measured in a closed loop around a source, and the wind velocity is measured, the pollutant mass emission rate (e. g. g sec^{-1}) of the source may be determined. The GFC, a passive device, is pointed upward and detects the thermal emission of the atmosphere (there is a small component of scattered solar radiation in daytime operation). This radiation is passed through a split cell (vacuum and a sample of gas being measured); the presence of the gas in the atmosphere is ideally indicated by a non-zero output from a detector which alternately views the atmosphere through the vacuum and gas cells. Sulfur dioxide is measured at $4 \mu\text{m}$, carbon monoxide at $4.6 \mu\text{m}$, and methane at $3.2 \mu\text{m}$.

7. 4. 2. 2 System Description

A schematic of the optical layout of the SAI GFC instrument for SO_2 , being developed for EPA⁽¹⁷⁷⁾ is shown in Fig. 7. 4. 2-1. It basically consists of an $f/1$ lens that focuses the incoming radiation onto a detector. A narrow bandpass optical filter confines the spectral response to the pollutant emission band. A high frequency chopper (f_1) is used to reduce $1/f$ noise. The gas cell, filled with $\text{SO}_2(\tau_G)$, and a reference aperture (τ_A) rotate in and out of the field of view at frequency f_2 . The mirror is operated (on command or continuously) by a stepping motor to permit successive viewing of the incoming radiation, reference source 1, or reference source 2. The reference sources are used to continuously update the balance of the instrument.

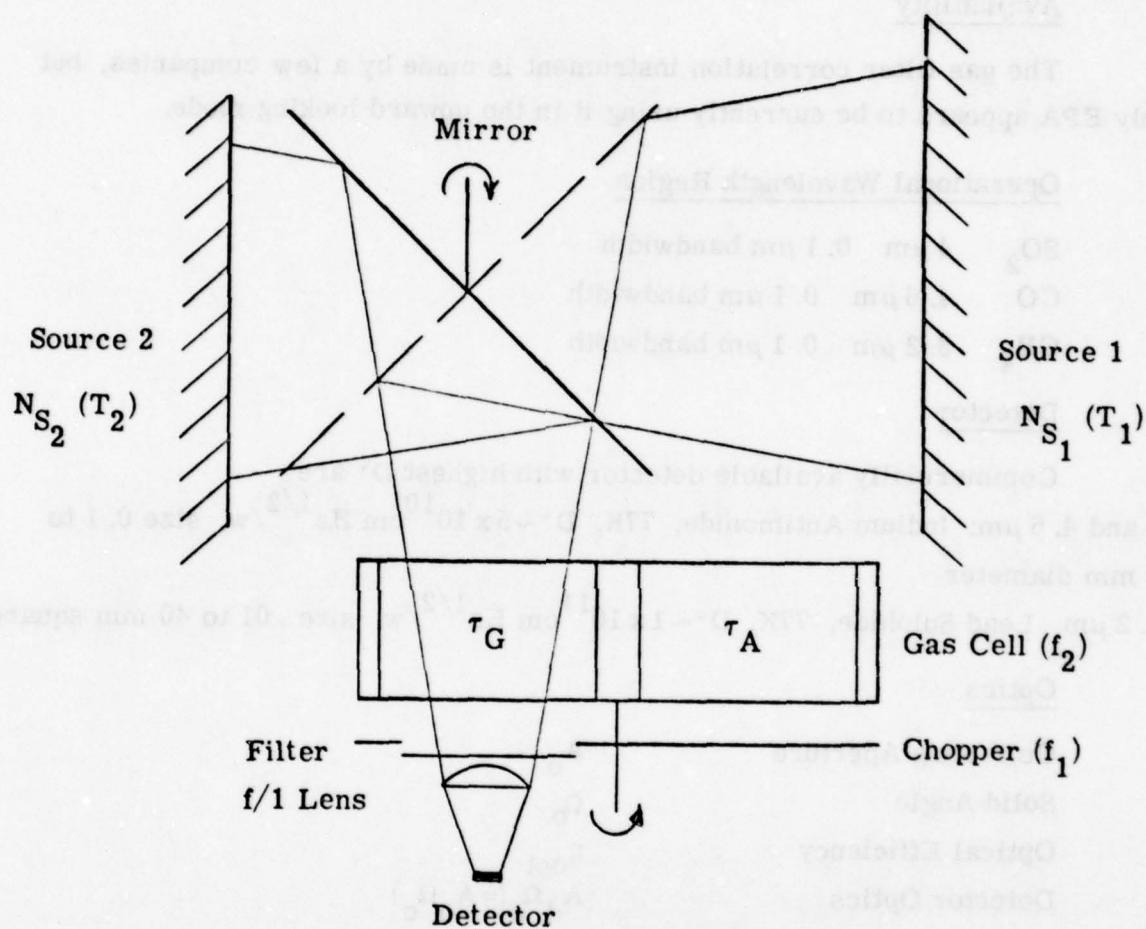


Figure 7. 4. 2-1. Optical Schematic of Up-Looking Instrument.

7. 4. 2. 3 System Parameters

Availability

The gas filter correlation instrument is made by a few companies, but only EPA appears to be currently using it in the upward looking mode.

Operational Wavelength Region

SO₂ 4 μm 0. 1 μm bandwidth
CO 4. 6 μm 0. 1 μm bandwidth
CH₄ 3. 2 μm 0. 1 μm bandwidth

Detector

Commercially available detector with highest D* are
4 and 4. 6 μm: Indium Antimonide, 77K, D*~5 x 10¹⁰ cm Hz^{1/2}/w, size 0. 1 to 3 mm diameter
3. 2 μm: Lead Sulphide, 77K, D*~1 x 10¹¹ cm Hz^{1/2}/w, size . 01 to 40 mm square

Optics

Collecting Aperture	A _o
Solid Angle	Ω _o
Optical Efficiency	η _{opt}
Detector Optics	A _d Ω _d (= A _o Ω _o)

These optical parameters are variables which must be chosen to fulfill the operational requirements.

7. 4. 2. 4 Theoretical Performance Prediction

The simplified calculations using radiances integrated over narrow spectral bandpasses, as done in Section 7. 4. 1. 4, cannot be utilized here

because the GFC instrument is based on correlation of the rotational structure in a rotation-vibration band. Thus the calculations have to be performed on a line-by-line basis using a large computer.

The signal to noise ratio for a detector-noise-limited GFC system is given by

$$\text{SNR} = \frac{\eta A_o \Omega_o \Delta V D^*}{\sqrt{A_d \Delta f}}$$

where ΔV is the GFC signal:

$$\Delta V = N^o(\lambda, T) \Delta \lambda M$$

where M is the modulation term which depends on the correlation of the rotational spectral structure.

These calculations have been done⁽⁵⁰⁾ for one pollutant, SO_2 , at two wavelengths 4 and 8.6 μm . The results of these calculations are given in Fig. 7. 4. 2-1 and may be compared to those for the tunable receiver (Fig. 7. 4. 1-3), showing the superior performance of the GFC. It is seen that the long wavelength region is more sensitive than the short wavelength region, and is also less influenced by the atmospheric temperature. However, the humidity and its distribution through the mixing layer introduce a large uncertainty at the long wavelength region. The following instrument parameters were used in the GFC calculations:

$$\begin{aligned} \eta &= 0.01 \\ A_d &= 0.23 \text{ cm}^2 \\ \Delta f &= 4.17 \times 10^{-3} \text{ Hz (60 sec time constant)} \\ D^*(4\mu\text{m}) &= 3 \times 10^{11} \text{ W}^{-1} \text{ Hz}^{1/2} \text{ cm} \\ D^*(8\mu\text{m}) &= 10^{10} \text{ W}^{-1} \text{ Hz}^{1/2} \text{ cm} \\ A_o \Omega_o &= 0.143 \text{ cm}^2 \text{ sr} \end{aligned}$$

Calculation Procedure

Because of the complexity (as explained above) of the calculation of the ΔV signal, we are restricted here to describing the effects of the instrument parameters on the resulting SNR. Also, we are restricted to the one pollutant, SO_2 , and to the atmospheric conditions which were assumed in the above calculation.

Analytical Procedure

Step 1: Using known or typical values of the proposed instrument, calculate

$$G = \frac{\eta A_{o \ o} D^*}{A_d \Delta_f}$$

The typical values used in the above-referenced calculation (i. e.,

$$\eta = 0.01$$

$$A_d = 0.23 \text{ cm}^2$$

$$A_f = 4.17 \times 10^{-3} \text{ Hz } (= 1/4 t_c)$$

$$D^* (4 \mu\text{m}) = 3 \times 10^{11} \text{ w}^{-1} \text{ Hz}^{\frac{1}{2}} \text{ cm}$$

$$D^* (8 \mu\text{m}) = 10^{10} \text{ w}^{-1} \text{ Hz}^{\frac{1}{2}}$$

$$A_{o \ o} = 0.143 \text{ cm}^2 \text{ sr}$$

can be used if actual values are not available.

Step 2: Using the value of G calculated in Step 1, calculate

$$k (4 \mu\text{m}) = 1.39 \times 10^{10} / G$$

$$k (8 \mu\text{m}) = 4.62 \times 10^9 / G$$

Step 3: From Figure 7.4.2-1, determine the "Minimum Detectable SO_2 Concentration". (SNR = 10)

Graphical Procedure

A graphical procedure is not presented because the computational variables are limited to the above instrument parameters.

Until further computer calculations are published, the atmospheric and pollutant parameters are limited to the ranges presented on Figure 7.4.2-1.

The reader is cautioned that this is a preliminary analysis of a developmental instrument.



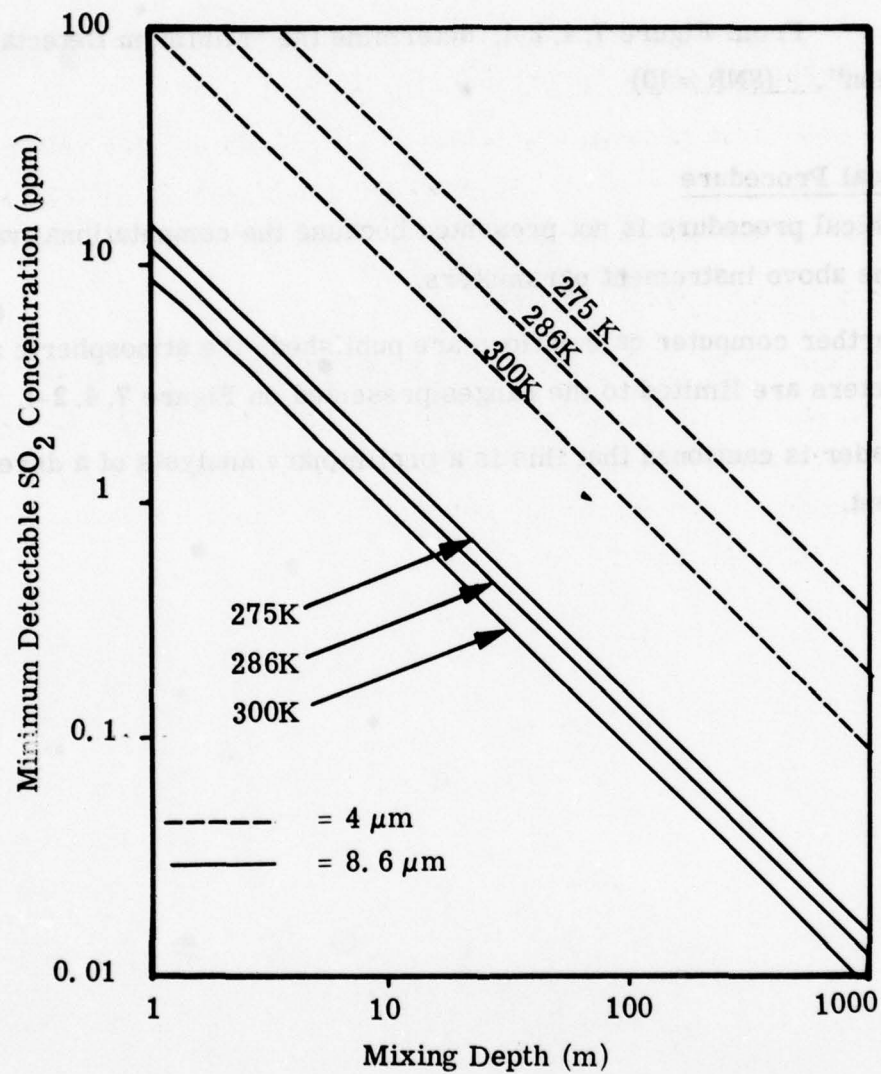


Figure 7. 4. 2-1. SO_2 Concentration Versus Mixing Depth for a GFC Instrument with SNR - 10 at Two Different Wavelength Regions

7. 4. 2. 5
7. 4. 2. 6 a

7. 4. 2. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. Special requirements applicable to particular pollutants are described in discussions of other monitors in Section 7.

7. 4. 2. 6 Data Analysis Procedures

The concentration of the pollutant is related to the output signal (ΔV) of the GFC instrument directly by laboratory and/or field calibrations. Typical calibration curves are shown in Fig. 7. 4. 2-3. The atmospheric temperature and layer thickness must be known to estimate the mean concentration of the pollutant.

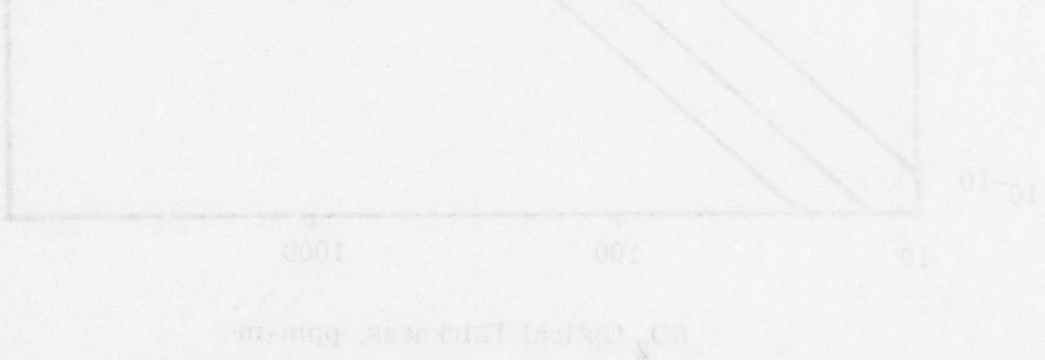


Figure 7.4.2-3. GFC signal as a function of SO_2 loading at 4 km for three temperatures

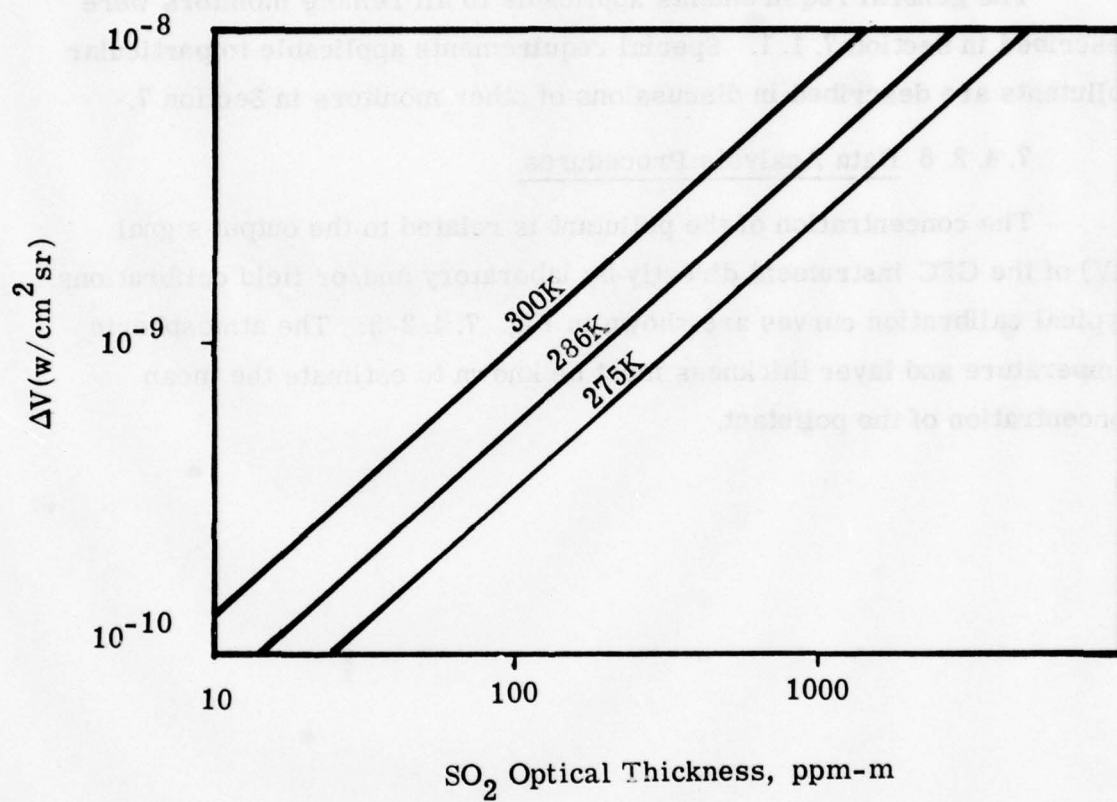


Figure 7. 4. 2-2. GFC Signal as a Function of SO_2 Loading at $4 \mu m$ for Three Temperatures

REFERENCES

- (1) "Jet Aircraft Emissions and Air Quality in the Vicinity of the Los Angeles International Airport," Air Pollution Control District County of Los Angeles, CA., April 1971.
- (2) "An Air Pollution Impact Methodology for Airports and Attendant Land Use," Argonne National Laboratory, APTD-1470 (January 1973).
- (3) "Air Quality Measurement at Atlanta International Airport Before and During Experimental Aircraft Taxiing Operations" - Final Report, EF-330, GEOMET, Inc. (June 1974).
- (4) "Airport Vicinity Air Pollution Study," Argonne National Laboratory, FAA-RD-73-113 (December 1973).
- (5) "Air Pollution at Heathrow Airport, London," SAE-DOT Conf. Aircraft, Washington, D. C., February 8-10, 1971.
- (6) K. Zeller, EPA-LV, private communication, September 1975.
- (7) 40 CFR 50
- (8) "Federal Air Quality Control Regions," EPA, Office of Air Programs, Publ. No. AP-102, January 1972.
- (9) "Aircraft Emissions: Impact on Air Quality and Feasibility of Control," EPA (no number, no date given).
- (10) "Analysis of Aircraft Exhaust Emission Measurements," Cornell Aeronautical Laboratory, NTIS--PB 204-879 (October 1971).
- (11) "USAF Aircraft Pollution Emission Factors and LTO Cycles," D. F. Naugle, and S. R. Nelson, AFWL-TR-74-303, (February 1975).
- (12) M. Platt, et al., "The Potential Impact of Aircraft Emissions on Air Quality," NREC Report No. 1167-1, (December 1971)
- (13) D. M. Fote, et al., "Airport Vicinity Air Pollution Study", FAA-RD-73-113, (December 1973)

- (14) J. E. Norco, et al., "An Air Pollution Impact Methodology for Airports and Attendant Land Use," APTD-1470, EPA, (January 1973).
- (15) "Air Quality Display Model," TRW Systems Group, NTIS PB-189194, (November 1969).
- (16) D. M. Rote, et al., "A Generalized Air Quality Assessment Model for Air Force Operations," AFWL-TR-74-304, (February 1975).
- (17) M. Sittig, "Pollution Detection and Monitoring Handbook," Noyes Data Corporation, Park Ridge, N. J. (1974).
- (18) E. R. Bartle, et al., "Development of HCl and HF Detection System", AFRPL-TR-71-59.
- (19) D. Burch, EPA-650/2-73-030 (1973).
- (20) A. R. Barringer, Proc. 4th Symp. Rem. Sens. (1966).
- (21) J. A. Decker, Appl. Optics 10, 510 (1971).
- (22) W. K. McGregor, et al., CIAP Rep. DOT-TSC-OST-73-4, p. 214.
- (23) J. A. Hodgeson, et al., in "Analytical Methods Applied to Air Pollution Measurements," Ann Arbor Science, eds. R. K. Stevens and W. F. Herget (1974), p. 43.
- (24) E. D. Hinkley and A. R. Calawa, *ibid.*, p. 55
- (25) L. G. Rosengren, Appl. Optics 14, 1960 (1975).
- (26) H. M. Segal, "Realistic Mixing Depths for Above Ground Aircraft Emissions", JAPCA 25, 1054 (1975).
- (27) H. W. Hiser, G. F. Andrews, and H. V. Senn, "Radar Measurement of Small Scale Turbulence and Thermal Stability in the Laser Atmosphere", JAPCA 25, 835 (1975).
- (28) J. Stuart Fordyce and Dean W. Sheibley, "Estimate of Contribution of Jet Aircraft Operations to Trace Element Concentration at or Near Airports", JAPCA 25, 721 (1975).

- (29) E. K. Bastress, "Impact of Aircraft Exhaust Emissions at Airports", Environ. Sci. Technol. 7, 811 (1973).
- (30) R. Dams, J. A. Robbins, K. A. Rahn, and J. W. Winchester, "Non-destructive Neutron Activation Analysis of Air Pollution Particulates", Anal. Chem. 42: 861 (1970).
- (31) R. E. Lee, Jr., S. S. Goranson, R. E. Ennone, and G. B. Morgan, "National Air Surveillance Cascade Impactor Network: II. Size Distribution Measurements of trace metal components," Environ. Sci. Technol. 6: 1025 (1972).
- (32) G. B. Morgan, G. Azolins, and E. C. Tabar, "Air Pollution Surveillance Systems", Science 170: 189 (Oct. 16, 1970).
- (33) R. B. King et al., Lewis Research Center, unpublished data obtained for the City of Cleveland.
- (34) R. T. H. Collis, and E. E. Uthe, "Mie Scattering Techniques for Air Pollution Measurement with Lasers", Opto-electronics 4, 87 (1972).
- (34a) R. M. Measures and G. Pilon, Opto-electronics 4, 141 (1972).
- (35) C. S. Cook, G. W. Bethke and W. D. Conner, Appl. Opt. 11, 1742 (1972).
- (36) W. D. Conner and J. R. Hodgkinson, P. H. S. Publ. 999-AP-30 (1967).
- (37) W. Conner, EPA, private communication (1975).
- (38) S. Nakahara, K. Ito, A. Fuke, S. Komatsu, H. Inaba, T. Kobayasi, Opto-electronics 4, 169 (1972).
- (39) E. E. Uthe and W. B. Johnson, "Lidar Observations of the Lower Troposphere Aerosol Structure During BOMEX", Final Report, SRI Project 7929 (1971).
- (40) R. T. H. Collis, Applied Optics 9, 1782 (1970).
- (41) E. E. Uthe and R. J. Allen, Optical and Quantum Electronics 7, 121 (1975).

- (42) P. B. Russell and E. E. Uthe, "The Mt. Sutro Tower Aerosol and Radiation Study", paper presented at Fall Annual Meeting of the American Geophysical Union, San Francisco, CA., 12-17 December 1974.
- (43) P. B. Russell and E. E. Uthe, "The Mt. Sutro Tower Aerosol and Radiation Study", presented at the 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (44) J. D. Spinhirne, B. M. Herman, and J. A. Reagan, "Monitoring of Tropospheric Aerosol Optical Properties by Lidar", presented at the 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (45) J. A. Reagan, D. M. Byrne, B. M. Herman, and R. L. Peck, "New Observations of Tropospheric Aerosols Made with the University of Arizona Bistatic Lidar", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (46) J. A. Reagan, J. D. Spinhirne, D. M. Byrne, and R. L. Peck, "Atmospheric Particulate Properties Inferred from Lidar and Solar Radiometer Observations Compared with In-Situ Aircraft Measurements: A Case Study", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (47) E. M. Patterson, G. W. Grams, and D. A. Gillette, "An Analysis of Laser Radar Backscatter Profiles Obtained During a Rural Boundary Layer Experiment", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (48) J. J. DeLuisi, B. G. Schuster and R. K. Sato, *Applied Optics* 14, 1917 (1975).
- (49) S. T. Shipley, J. A. Weinman, "Design Considerations for a High Spectral Resolution Lidar", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (50) W. R. McNeil and A. I. Carswell, *Applied Optics* 14, 2158 (1975).
- (51) A. I. Carswell, S. R. Pal and J. S. Ryan, "Lidar Scattering in Turbid Media", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.

- (52) R. W. L. Thomas and A. C. Holland, "A Monte Carlo Simulation of the Depolarization of Lidar Signals by Clouds", and "Maximum Sky Polarization: A supplement to Laser Atmospheric Studies—More Results", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (53) K. Sassen, "A Comparison of Hydrometeor Linear Depolarization Ratios from CW Laser and Lidar Systems", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (54) 39FR32094, September 4, 1974.
- (55) F. S. Harris, Jr., Appl. Optics 11, 2697 (1972).
- (55a) G. M. Hidy and S. K. Friedlander, "The Nature of the Los Angeles Aerosol", Proc. 2nd Intern. Clean Air Congr., eds. H. M. Englund and W. T. Beary, Academic Press, New York and London, p. 391 (1971).
- (56) M. Griggs, JAPCA 22, 356 (1972).
- (57) L. Elterman, Applied Optics 9, 1804 (1969).
- (58) Schotland, R. M., J. Appl. Meteorol. 13, 71 (1974).
- (59) C. B. Ludwig and M. Griggs, "Application of Remote Monitoring Techniques in Air Enforcement", Final Report, EPA 68-03-2137, SAI-75-638-LJ (April 1975).
- (60) K. W. Rothe, U. Brinkmann and H. Walther, Appl. Phys. 3, 115 (1974a).
- (61) K. W. Rothe, U. Brinkmann and H. Walther, Appl. Phys. 4, 181 (1974b).
- (62) W. B. Grant, R. D. Hake, Jr., E. M. Liston, R. C. Robbins and E. K. Proctor, Jr., Appl. Phys. Lett. 24, 550 (1974).
- (63) T. Igarashi, 5th Conference on Laser Radar Studies, Williamsburg, Virginia (June 1973).
- (64) S. Zaromb, Pittsburg Conference, Cleveland (March 1974).

- (65) V. L. Granatstein, M. Rhinewine and A. H. Fitch, Appl. Opt. 12, 1511 (1973).
- (66) S. A. Ahmed, Appl. Opt. 12, 901 (1973).
- (67) R. L. Byer and M. Garbuny, Appl. Opt. 12, 1497 (1973).
- (68) W. B. Grant and R. D. Hake, Jr., Journal of Applied Physics 46, 3019 (1975).
- (69) H. Inomata and T. Igarashi, Radio Research Laboratories, Tokyo, Preprint, private communication (1974).
- (70) K. Asai and T. Igarashi, Preprint, private communication (1974).
- (71) T. Kobayasi and H. Inaba, Optical and Quantum Electronics 7, 319 (1975).
- (72) J. M. Hoell, Jr., W. R. Wade, and R. T. Thompson, Jr.: Remote Sensing of Atmospheric SO₂ Using the Differential Absorption Lidar Technique. Proceedings of the International Conference on Environmental Sensing and Assessment, Las Vegas, Nevada, September 14-19, 1975.
- (73) W. R. Wade, J. M. Hoell, Jr., and R. T. Thompson, Jr., "A Lidar System for the Measurement of Tropospheric SO₂ Using the Dial Technique", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (74) E. E. Remsberg, L. Gordley, S. K. Poultney and R. T. Thompson, "Analysis of Differential Absorption Lidar Measurements from Shuttle", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (75) M. L. Wright, E. K. Proctor, L. S. Gasiorek, and E. M. Liston: A Preliminary Study of Air Pollution Measurement by Active Remote Sensing Techniques. Contract Report NAS1-11657 (1975).
- (76) C. H. Bair and F. Allario, "Analysis of the Sensitivity of Near IR Dial for Measurements of HCl in the Ground Cloud of SRM's and for Profiling Atmospheric Pollutants", presented at 7th International Laser Radar Conference, SRI, Nov. 4-7, 1975.

- (77) R. K. Dumbauld, R. J. Bjorklund and J. F. Bowers, "NASA/MSFC Multilayer Diffusion Models and Computer Program for Operational Prediction of Toxic Fuel Hazards", NASA CR-129006 (June 1973).
- (78) T. J. McIlrath, M. B. Marris and R. W. Gammon, "Tunable Laser for Water Vapor Lidar", presented at 7th International Laser Radar Conference, SRI, Nov. 4-7, 1975.
- (79) T. Wilkerson, L. Cotnoir III and G. Schwemmer, "Water Vapor Lidar: Calibration and Simulation", presented at 7th Int'l Laser Radar Conference, SRI, November 4-7, 1975.
- (80) D. Herriott and H. J. Schulte, Appl. Optics 4, 883 (1965).
- (81) E. R. Murray, R. D. Hake, Jr., J. E. van der Laan, and J. G. Hawley, "Atmospheric Water Vapor Measurements with a 10- μ m Dial System", presented at 7th Int'l Laser Radar Conference, SRI, Nov. 4-7, 1975; App. Physics Ltrs. 28, 542.
- (82) W. B. Grant, J. G. Hawley, R. D. Hake, Jr., and R. G. March, "Backscatter Fluctuations Observed with a Variable-Delay Dual-Pulse Lidar", presented at 7th Int'l Laser Radar Conference, SRI, Nov. 4-7, 1975.
- (83) J. B. Marling, J. G. Hawley, E. M. Liston, and W. B. Grant, "Lasing Characteristics of Seventeen Visible-Wavelength Dyes Using a Coaxial-Flashlamp-Pumped Laser", Applied Optics 13, 2317 (1974).
- (84) H. Kildal and R. L. Byer, Proc. IEEE 59, 1644 (1971).
- (85) T. Hirschfeld and S. Klainer, "Remote Raman Spectroscopy as a Pollution Radar", Optical Spectra, p. 63 (July/August 1970).
- (86) C. M. Penney, L. M. Goldman, and M. Lapp, "Raman Scattering Cross Sections," Nature Physical Science 235, 110 (1972).
- (87) D. G. Fouche and R. K. Chang, "Relative Raman Cross Section for N₂, O₂, CO, CO₂, SO₂, and H₂S," Appl. Phys. Letters 18, 579 (1971).
- (88) W. Arden, et. al., Remote Raman Detection Study Instrument, 6th Quarterly Progress Report, Edgewood Arsenal Contract DAAA15-70-C-0418 (1972).

- (89) H. P. DeLong, "Air Pollution Field Studies with a Raman Lidar", *Optical Engr.* 13, 5 (1974).
- (90) H. Inaba and T. Kobayasi, *Opto-Electr.* 4, 101 (1972).
- (91) S. H. Melfi, J. D. Lawrence, and M. P. McCormick, "Observation of Raman Scattering by Water Vapor in the Atmosphere," *Appl. Phys. Letters* 15, 295 (1969).
- (92) W. H. Smith, "A New Method for the Detection of Raman Scattering from Atmospheric Pollutants", *Opto-Electr.* 4, 161 (1972).
- (93) J. J. Barrett, "The Use of a Fabry-Perot Interferometer for Studying Rotational Raman Spectra of Gases" in *Laser Raman Gas Diagnostics*, p. 63, eds. M. Lapp and C. M. Penney, Plenum Press, New York and London; (1974).
- (94) S. M. Klainer, "Advances in Remote Gas Analysis Using Fabry-Perot Techniques", p. 86 in *Proc. Soc. Photo-Opt. Instr. Eng.*, Vol. 49, Impact of Lasers in Spectroscopy, San Diego, CA., August 19-20, 1974.
- (95) J. A. Gelbwaches and M. Birnbaum, *Applied Optics* 12, 2442 (1973).
- (96) D. A. Leonard and B. Caputo, "A Single-ended Atmospheric Transmissometer", *Opt. Engr.* 13, 11 (1974).
- (97) D. D. Dylis, "A Raman Technique for the Remote Measurement of Aqueous Acid Solutions," p. 156 in *Proc. Soc. Photo-Opt. Instr. Eng.*, Vol. 49, Impact of Lasers in Spectroscopy, San Diego, CA., August 19-20, 1974.
- (98) S. K. Poultney, M. L. Brumfield and J. H. Siviter, Jr., "Quantitative Remote Measurements of Pollutants from Stationary Sources Using Raman Lidar", presented at the 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (99) D. A. Leonard, "Raman and Fluorescence Measurements of Combustion Emission," p. 110 in *Proc. Soc. Photo-Opt. Instr. Eng.*, Vol. 49, Impact of Lasers in Spectroscopy, San Diego, CA., August 19-20, 1974.
- (100) Lt. G. E. Bresowar and D. A. Leonard, "Measurement of Gas Turbine Exhaust Pollutants by Raman Spectroscopy," AIAA Paper No. 73-1276 (Nov. 1973).

- (101) V. E. Derr and C. G. Little, *Appl. Optics* 9, 1976 (1970).
- (102) T. Hirschfeld, E. R. Schildkraut, H. Tannenbaum and D. Tannenbaum, *Appl. Phys. Lett.* 22, 38 (1973).
- (103) P. F. Williams, D. L. Rousseau, and S. H. Dworesky, *Phys. Rev. Lett.* 32, 196 (1974).
- (104) H. Rosen, P. Robrish and O. Chamberlain, *Applied Optics* 14, 2703 (1975).
- (105) W. Holzer, W. F. Murphy and H. J. Bernstein, *J. Chem. Phys.* 52, 399 (1970).
- (106) C. C. Wang and L. I. Davis, *Phys. Rev. Lett.* 32, 349 (1974).
- (107) R. L. St. Peters, S. D. Silverstein, W. M. Morey and D. J. Taylor, "Raman Scattering Studies," General Electric, Final Technical Report SRD-73-033 (February 1973).
- (108) C. M. Penney, "Light Scattering and Fluorescence in the Approach to Resonance—Stronger Probing Processes," p. 191, in "Laser Raman Gas Diagnostics," ed. M. Lapp and C. M. Penney, Plenum Press, New York and London, (1974).
- (109) W. Kiefer, "Penney Discussion", p. 215 in "Laser Raman Gas Diagnostics," ed. M. Lapp and C. M. Penney, Plenum Press, New York and London, (1974).
- (110) M. L. Wright, E. K. Proctor, L. S. Gasiorek and E. M. Liston, "A Preliminary Study of Air Pollution Measurement by Active Remote-Sensing Techniques," NASA CR-132724 (June 1975).
- (111) R. L. Byer, *Opt. Quant. Electr.* 7, 147 (1975).
- (112) M. R. Bowman, A. J. Gibson and M. C. W. Sandford, *Nature* 221, 456 (1969).
- (113) A. J. Gibson, *J. Sci. Instr.* 2, 802 (1969).
- (114) A. J. Gibson and M. C. W. Sandford, *Nature* 239, 509 (1972).
- (115) F. Felix, W. Keenlside, G. Kent and M. C. W. Sandford, *Nature* 246, 345 (1973).

- (116) S. Nakahara, K. Ito and S. Iot, Abstracts from 5th Conference
Laser Radar Studies, Williamsburg, Virginia (June 1973).
- (117) M. C. Fowler and P. J. Berger, "Feasibility Study of the Use of
Resonance Scattering for the Remote Detection of SO_2 ",
EPA-650/2-74-020 (Jan. 1974).
- (118) J. W. Robinson and J. D. Dake, Spectr-Lett. 6, 685 (1973).
- (119) J. W. Robinson and J. D. Dake, Anal. Chem. Acta 71, 277 (1974).
- (120) I. M. Pikus, H. W. Goldstein and T. R. Riethof, "The Remote
Measurement of NO from an Airplane or Space Platform,"
AIAA Paper 71-1112 (Nov. 1971).
- (121) R. T. Menzies, Appl. Optics 10, 1532 (1971).
- (122) C. M. Penney, W. W. Morey, R. L. Peters, S. D. Silverstein,
M. Lapp and D. R. White, NASA CR-132363 (Sept. 1973).
- (123) J. A. Gelbwachs, M. Birnbaum, A. W. Tucker and C. L. Finder,
Opto-electronics 4, 155 (1972).
- (124) J. A. Gelbwachs and M. Birnbaum, Appl. Optics 12, 2442 (1973).
- (125) D. G. Fouche and R. K. Chang, Phys. Rev. Lett. 29, 536 (1972).
- (126) R. L. St. Peters, S. D. Silverstein, M. Lapp, and C. M. Penney,
Phys. Rev. Lett. 30, 191 (1973).
- (127) R. L. St. Peters and S. D. Silverstein, Opt. Commun. 7, 193 (1973).
- (128) M. Berjot, M. Jacon and L. Bernard, Opt. Comm. 4, 117 (1971);
Can. J. Spectr. 17, 60 (1972).
- (129) P. Robrish, H. J. Rosen, and O. Chamberlain, "Observation of a
Continuous Transition from Resonance Raman Scattering to
Fluorescence," U. C. Berkeley (submitted for publication).
- (130) E. L. Baardsen and R. W. Terhune, Appl. Phys. Lett. 21, 209
(1972).
- (130a) M. L. Streiff and C. B. Ludwig, "Remote Sensing of Air Pollution
in Urban Areas," EPA-650/2-73-026 (August 1973).
- (131) T. Hirschfeld, "Tunable Laser, Good and Bad," Optical Spectra,
p. 23 (Aug. 1974).

- (131a) J. Kuhl and W. Schmidt, Appl. Phys. 3, 251 (1974)
- (132) E. D. Hinkley, "Development of In-Situ Prototype Diode Laser System to Monitor SO₂ Across the Stack," MIT-Lincoln Laboratory, Final Report, EPA-R2-73-218 (May 1973).
- (133) G. K. Klauminzer, "New Dye Laser Applications," Electro-Opt. Sys. Des., p. 25 (Dec. 1974).
- (134) O. R. Wood, "High Pressure Molecular Lasers," Proc. IEEE 62, 355 (1974).
- (135) R. V. Hess and R. K. Seals, Jr., "Applications of Tunable High Energy/Pressure Pulsed Lasers to Atmospheric Transmission and Remote Sensing," NASA TM X-7201 (Sept. 1974).
- (136) R. L. Abrams and W. B. Bridges, "Characteristics of Sealed-Off Waveguide CO₂ Lasers," IEEE J. Quant. Electr. QE9, 940 (1973).
- (137) R. L. Byer, "Parametric Oscillators," from Laser Spectroscopy, eds. R. G. Brewer and A. Mooradian, Plenum Pub. Co., New York (1974).
- (138) R. L. Byer, R. L. Herbst, and R. N. Fleming, "A Broadly Tunable IR Source," Appl. Phys. Dept., Stanford University, private communication, (1975).
- (139) C. K. N. Patel, "Tunable Spin-Flip Raman Laser and High Resolution IR Spectroscopy," presented at the Pittsburgh Conf. in Cleveland, Paper No. 325, March 4-8 (1974).
- (140) "Spin-Flip Device Could Play Role in SST Story," Electronics, p. 32, (Sept. 13, 1971).
- (141) Reserved
- (142) Reserved
- (143) W. A. McClenny, R. E. Baumgardner, Jr., F. W. Baity, and R. A. Gray, JAPCA 24, 1044 (1974).
- (144) T. B. Hirschfeld, Opt. Engineering 13, 15 (1974).

- (145) J. J. Ball and R. A. Keller, JAPCA 25, 631 (1975).
- (146) D. C. O'Shea and L. G. Dodge, Appl. Optics 13, 1481 (1974).
- (146a) C. B. Ludwig, R. Bartle, and M. Griggs, "Study of Air Pollutant Detection by Remote Sensors," NASA CR-1380 (July 1969).
- (147) Z. Kucеровsky, E. Brannen, K. C. Paulekat and D. G. Rumbold, J. Appl. Meteor. 12, 1387 (1973).
- (148) S. E. Craig, D. R. Morgan, D. L. Roberts and L. R. Snowman, "Development of a Gas Laser System to Measure Trace Gases by Long Path Absorption Techniques," EPA-650/2-74-046a, June 1974.
- (149) W. A. McClenny, F. W. Baity, Jr., R. E. Baumgardner, Jr., R. A. Gray, R. J. Gillmeister and L. R. Snowman, "Development of a Gas Laser System to Measure Trace Gases by Long Path Absorption Techniques, Vol. II - Field Evaluation of Gas Laser System for Ozone Monitoring," EPA-650/2-74-046-b (July 1974).
- (150) E. D. Hinkley and R. T. Ku, "Diode Laser Multi-Pollutant Ambient Air Monitoring," NSF/RANN/IT/GI-37603 (June 1974).
- (151) R. T. Ku, E. D. Hinkley, and J. O. Sample, Appl. Optics 14, 854 (1975).
- (152) E. D. Hinkley, "Bistatic Monitoring of Gaseous Pollutants with Tunable Semiconductor Lasers," presented at the 1974 Pittsburgh Conf. on Anal. Chem. Appl. Spectr., Cleveland, Ohio (March 1974).
- (153) E. D. Hinkley and R. T. Ku, "Long-Path Ambient-Air Monitoring with Tunable Lasers—Participation in the St. Louis Regional Air Pollution Study (RAPS) of EPA," Proc. 2nd Ann. NSF-RANN Trace Contaminants Conf., Asilomar, CA (Aug. 1974).
- (154) R. T. Menzies and M. S. Schumate, JPL, private communication, (Sept. 1975).
- (155) R. T. Menzies and M. S. Schumate, Science 184, 571 (1974).
- (156) R. T. Menzies and M. T. Chahine, Appl. Optics 13, 2840 (1974).

- (157) S. H. Melfi, G. B. Morgan, J. L. Guagliardo and J. Koutsandreas, Proc. IEEE, National Aerospace and Electr. Conf., Dayton, Ohio (May 1974).
- (158) R. K. Selas and C. H. Bair, ISA JSP 6675, presented at 2nd Joint Conf. Sens. Env. Pollutants, Washington, D. C. (Dec. 1973).
- (159) L. R. Snowman and R. J. Gillmeister, "A Laser Policeman for Dirty Air," Optical Spectra, p. 30 (June 1972).
- (160) "3-D Study Provides Look at Upper Atmosphere," California Air Resources Board, Bulletin 6, 7 (May 1975).
- (161) "Laser Safety Guide," Laser Safety Committee of the Laser Institute of America, 4100 Executive Park Drive, Cincinnati, Ohio 45241 (Issued in 1974).
- (162) J. Topping, "Errors of Observation and Their Treatment," Science Paperbacks, Chapman and Hall LTD, 3rd Ed. (1962).
- (163) L. R. Snowman and R. J. Gillmeister, "Infrared Laser System for Extended Area Monitoring of Air Pollution," AIAA Paper 71-1059.
- (164) E. R. Ochs and R. S. Lawrence, ESSA Tech. Report ERL 106-WP16, Boulder, Colorado (Febr. 1969).
- (165) M. L. Streiff and C. L. Claysmith, "Design and Construction of a System for Remote Optical Sensing of Emissions," EPA-R2-72-052 (Oct. 1972).
- (166) "Air Pollution Measurements in the Infrared," General Dynamics, ElectroDynamic Division, TM 6-125PH-336 (Sept. 1971), included as Appendix I in Ref. 130a.
- (167) G. N. Plass, J. Opt. Soc. Am. 48, 690 (1958).
- (167a) S. S. Penner, "Quantitative Molecular Spectroscopy and Gas Emissivities," Addison-Wesley Publishing Co., Inc., Reading, Mass. (1959).
- (168) C. B. Ludwig, Appl. Optics 10, 1057 (1971).
- (169) V. E. Derr, M. H. Ackley, M. J. Post, and R. F. Calfee, "Calculation of the Concentrations of Atmospheric Gases from Long Path Infrared Absorption Spectra by a Least Squares Method," under Contract Agreement No. EPA-IAG-077(D).

- (170) R. A. Sawyer, "Experimental Spectroscopy," Dover Publications, Inc., New York, 3rd Edition (1963).
- (171) J. A. Decker, Jr., Appl. Optics 10, 510 (1971).
- (172) Larson, N. M., Crosmun, R., and Talmi, Y., Appl. Opt. 13, 2662, (1974).
- (173) L. Mertz, "Transformation in Optics," Wiley, New York (1965).
- (174) W. H. Steel, "Interferometry," Cambridge U. P., Cambridge (1967).
- (175) L. L. Acton, M. Griggs, G. D. Hall, C. B. Ludwig, W. Malkmus, W. D. Hesketh and H. Reichle, "Remote Measurement of Carbon Monoxide by a Gas Filter Correlation Instrument," AIAA J. 11, 899 (1973).
- (176) C. B. Ludwig, M. Griggs, W. Malkmus and E. R. Bartle, "Air Pollution Measurements from Satellites," NASA CR-2324 (Nov. 1973).
- (177) "Development of Gas Filter Correlation Instruments for Extended Area Stationary Source Gaseous Pollutant Measurements," EPA Contract 68-02-1798.
- (178) Barnes, H. M., Herget, W. F. and Robbins, R. "Analytical Methods Applied to Air Pollution Measurements," p. 245, Ann Arbor Science Publishers, Inc., (August 1974).
- (179) W. F. Herget, H. M. Barnes, Jr., C. B. Ludwig and G. W. Ashley, "Infrared Spectra of Pollutant Emissions from Various Stationary Sources," AIAA Paper No. 71-1082 (Nov. 1971).
- (180) A. Prostack and R. H. Dye, "Long-Path Spectrophotometric Instrumentation for In-Situ Monitoring of Gaseous Pollutants in the Urban Atmosphere," Bendix; Aerospace Systems Division, BSR 3027 (Oct. 1970).
- (180a) E. D. Hinkley and P. L. Kelley, "Detection of Air Pollutants with Tunable Diode Lasers," Science.
- (181) E. R. Bartle, "Infrared Sensor for the Remote Monitoring of SO₂," EPA-650/2-75-041 (May 1975).
- (182) E. D. Hinkley, "Tunable Infra-red Lasers and Their Applications to Air Pollution Measurements," Opto-electronics 4, 69 (1972).

- (183) R. T. Menzies, "Remote Sensing with Infrared Heterodyne Radiometers," *Opto-electronics* 4, 179 (1972).
- (184) R. T. Menzies and M. S. Shumate, "Air Pollution: Remote Detection of Several Pollutant Gases with a Laser Heterodyne Radiometer," *Science* 184, 570 (1974).
- (185) R. K. Seals, "Analysis of Tunable Laser Heterodyne Radiometry: Remote Sensing of Atmospheric Gases," *AIAA J.* 12, 1118 (1974).
- (186) M. C. Teich, *Proc. IEEE* 56, 37 (1968).
- (187) A. E. Siegman, *Proc. IEEE* 54, 1350 (1966).
- (188) R. T. Menzies, *Appl. Optics* 10, 1532 (1971).
- (189) H. Walter, Jr. and D. Flanigan, *Appl. Optics* 14, 1423 (1975).
- (190) B. Noble, "Applied Linear Algebra," Prentice-Hall, Englewood Cliffs, N. J. (1969).
- (191) D. Flanigan and H. DeLong, *Appl. Optics* 10, 51 (1971).
- (192) A. R. Barringer and J. P. Schock, *Proc. 4th Symp. Rem. Sens. Environ.*, U. Michigan, p. 779 (1966).
- (193) G. S. Newcomb and M. M. Millian, *IEEE Trans. Geosci. Electr.* GE-8, 149 (1970).
- (194) M. M. Millan, S. J. Townsend and J. Davies, "Study of the Barringer Refractor Plate Correlation Spectrometer as a Remote Sensing Instrument," Toronto, UTIAS Report, No. 146 (August 1970).
- (195) C. R. McCreight and C. L. Tien, "Interpretation Problems in the Correlation-Mash Sensing Technique," Paper No. 71-1061, Joint Conference on Sensing of Environmental Pollutants, Palo Alto, California (Nov. 8-10, 1971).
- (196) C. B. Ludwig, M. Griggs, W. Malkmus and E. R. Bartle, *Appl. Optics* 13, 1494 (1974).
- (197) R. A. McClatchey, W. S. Benedict, S. A. Clough, D. E. Burch, R. F. Calfee, K. Fox, L. S. Rothman, J. S. Garing, "AFCRL Atmospheric Absorption Line Parameters Compilation," AFCRL-TR-73-0096 (26 Jan. 1973).

- (198) J. N. Hamilton, J. A. Rowe and D. Anding, "Atmospheric Transmission and Emission Program," Aerospace Rep. No. TOR-0073(3050-02)-3 (15 June 1973).
- (199) J. E. A. Selby and R. A. McClatchey, "Atmospheric Transmittance from 0.25 to 28.5 μ m: Computer Code LOWTRAN 2," AFCRL-72-0745 (29 Dec. 1972).
- (200) H. J. Bolle, "The Influence of Atmospheric Absorption and Emission on Infrared Detection Range," Infrared Physics 5, 115 (1965).
- (201) M. Gutnick, "Aids for Computing Stratospheric Moisture," GRD Research Notes No. 50, AFCRL 203 (1961).
- (202) A. E. Siegman, Appl. Optics 5, 1588 (1966).
- (203) M. C. Teich, Proc. IEEE 56, 37 (1968).
- (204) W. L. Smith, Appl. Optics 9, 1993 (1970).
- (205) J. Y. Wang, J. Atmos. Sci. 31, 513 (1974).
- (206) A. Betz, "Laser Heterodyne Spectroscopy in Astronomy," Paper FB7-1, presented at "Applications of Laser Spectroscopy," Spring Conf. of Opt. Soc. Amer. at Anaheim, Calif., (March 19-21, 1975).
- (207) M. M. Abbas, M. J. Mumma, T. Kostiak and D. Buhl, "Sensitivity Limits of an Infrared Heterodyne Spectrometer for Astrophysical Applications," Appl. Optics 15, 427 (1976).
- (208) A. J. Hoffman, T. C. Curran, T. B. McMullen, W. M. Cox, and W. F. Hunt, Jr., "EPA's Role in Ambient Air Quality Monitoring," Science 190, 243 (1975).
- (209) "Ambient Air Monitoring Reference and Equivalent Methods," 40FR7042 (18 Feb. 1975).
- (210) 41FR3893 (January 27, 1976).
- (211) 41 FR5144 (February 4, 1976).
- (212) 41FR11263 (March 17, 1976).

- (213) "Guideline Specifications for the Development of Instruction Manuals for Automatic Air Monitoring Instruments," National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151.
- (214) An example manual based on the above report and titled "Fully Proceduralized Instruction Manual for the Bendix Ozone Monitor, Model 8002" is available from the same source.
- (215) A. Daniels and W. Bach, "Simulation of the Environmental Impact of an Airport on the Surrounding Air Quality," J. Air. Poll. Contr. Ass. 26, 339-344 (1976).
- (216) A. Daniels, R. H. Jones, and W. Back, "Determination of Patterns of Average and Maximum Air Pollutant Levels in Urban Areas," Proc. Conf. Urban Env. and 2nd Conf. Biomet. 114-119 (1972).
- (217) R. Jones, A. Daniels, and W. Bach, "Fitting a Circular Distribution to a Histogram," J. Appl. Meteorol. 15: (1976).
- (218) L. M. Shabad and G. A. Smirnov, "Aircraft Engines as a Source of Carcinogenic Pollution of the Environment," Atmos. Environ. 6:153(1972).
- (219) J. A. Fay, "Air Pollution from Future Giant Jetports," Paper No. 70-78, 63rd Annual Meeting, APCA, St. Louis, 1970.
- (220) R. P. Carter and C. J. Gregory, "A Mathematical Diffusion Model with Respect to a Moving Aircraft," Paper No. 71-129, 64th Annual Meeting, APCA Atlantic City, 1971.
- (221) R. E. George, J. S. Nevitt, and J. A. Verssen, "Jet Aircraft Operations: Impact on the Air Environment," J. Air Poll. Control Assoc. 22:509 (1972).
- (222) R. Cirillo, J. F. Tschanz, and J. E. Camaioni, "Aircraft Control Measures for Emission Reduction," J. Air Poll. Contr. Ass. 26, 500 (1976).
- (223) I. T. Wang, D. M. Rote, L. A. Conley, "Airport Vicinity Air Pollution Study--Model Application and Validation and Air Quality Impact Analysis at Washington National Airport," Argonne National Laboratory, Report No. FAA-RD-74-132, Federal Aviation Administration, Washington, D. C., July 1974.

- (224) L. E. Wangen, et al., "A Generalized Air Quality Assessment Model for Air Force Operations--An Operator's Guide," Argonne National Laboratory, Report No. TR-74-54, Air Force Weapons Laboratory, Kirtland AFB, N. M., to be published.
- (225) D. M. Rote and L. E. Wangen, "A Generalized Air Quality Assessment Model for Air Force Operations--Technical Report," Argonne National Laboratory, Air Force Weapons Laboratory, Kirtland AFB, N. M., to be published.
- (226) J. T. MacWaters, R. C. Koch, and S. D. Thayer, "Air Quality Measured at Atlanta International Airport before and during Experimental Aircraft Taxiing Operations," GEOMET Report No. EF-330, June 1974.
- (227) "Review of Atlanta Aircraft Ground Emissions Control Demonstration," Mitre Corp., McLean, Va., to be published.
- (228) R. R. Cirillo, J. F. Tschanz, J. E. Camaioni, "An Evaluation of Strategies for Airport Air Pollution Control," Report No. EPA-450/3-75-052, U. S. Environmental Protection Agency, Research Triangle Park, N. C., January 1975.
- (229) J. S. Nader, F. Jaye and W. Conner, "Performance Specifications for Stationary-Source Monitoring Systems for Gases and Visible Emissions," EPA-650/2-74-013 (January 1974).
- (230) Request for Proposal, EPA, DU-76-A157 (April 23, 1976).
- (231) E. E. Hughes, "Development of Standard Reference Materials for Air Quality Measurement," presented at Instr. Soc. Am., Instrumentation-Automation Conference, New York, N. Y., October 28-31, 1974.
- (232) H. G. McAdie and F. J. Hopton, "The Need for Practical Standards in Air Pollution Measurement," American Laboratory (December 1975).
- (233) R. J. Bryan, P. C. Kochis, J. W. Boyd, M. L. McQueary and R. L. Norton, "Guidelines for Enforcement and Surveillance of Supplementary Control Systems," EPA-340/1-75-008 (September 1975).

(The material dealing with meteorological instruments is excerpted from the 1975 Revision of the Air Pollution Training Institute, Course 435, Atmospheric Sampling, Chapter XXIII).

- (234) E. O. Doebelin, Measurement Systems: Application and Design, McGraw-Hill Co., New York.
- (235) E. W. Hewson, "Meteorological Measurements," Air Pollution, Vol. II, New York, Academic Press.
- (236) W. E. K. Middleton and A. F. Spilhaus, Meteorological Instruments, Toronto, University of Toronto Press, 1953.
- (237) A. C. Stern, Editor, Air Pollution Second Edition Vol. II, New York, Academic Press, 1968.
- (238) R. H. Dieck, and J. H. Elwood, "The Assessment of Emission Analysis Accuracy," presented at the 67th Annual APCA Meeting in Denver, CO., June 9-13, 1974.
- (239) P. K. Stein, "Classification Systems for Transducers and Measuring Systems," Symposium on Environmental Measurements, U. S. Dept. HEW, July 1964.
- (240) T. J. Lockhart, "Bivanes and Direct Turbulence Sensors," Meteorology Research Inc., MRI 170 Pa 928, June 1970.
- (241) H. Klingenberg, M. Fock, K. -H. Lies and L. Pazsitka, "A Critical Study of the United States Exhaust Emission Certification Test--Error Analysis for the Test Procedure," presented at the 67th Annual APCA Meeting in Denver, CO., June 9-13, 1976.
- (242) R. T. Ku and E. D. Hinkley, "Long-Path Monitoring of Atmospheric Carbon Monoxide", (1975 RAPS, St. Louis, Missouri), NSF/RANN/IT/GI-37603, (April 1976).
- (243) E. D. Hinkley, "Laser Spectroscopic Instrumentation and Techniques: Long-Path Monitoring by Resonance Absorption", Optical and Quantum Elec. 8, 155-167 (1976).
- (244) "Pollution Monitor has 10 km Range", Industrial Research, p. 14 (July 1976).
- (245) AWST, (May 31, 1976).
- (246) W. Herget, "Long-Path Measurements of CO Concentrations at Williams Air Force Base", Interim Report, (April 19, 1976).

- (247) R. H. Dieck and J. H. Elwood, "The Assessment of Emission Analysis Accuracy", JAPCA 25, 845 (1975).
- (248) M. C. Natrella, "Experimental Statistics", NBS Handbook Number 91, (1963).
- (249) E. R. Murray, "Remote Measurement of Gases Using Discretely Tunable Infrared Lasers", presented at the 20th SPIE Symposium, Paper 95-15, San Diego, CA., August 24-27, (1976); Optical Engineering 16, 284.
- (250) D. J. Spencer, G. C. Denault, and H. H. Takimoto, "Atmospheric Gas Absorption at DF Laser Wavelengths", Appl. Opt., Vol. 13, p. 2855 (1974).
- (251) R. T. Menzies and M. S. Shumate, "Remote Measurements of Ambient Air Pollutants with a Bistatic Laser System", Appl. Opt. 15, 2080 (1976).
- (252) P. Beckmann and A. Spizzichino, "The Scattering of Electromagnetic Waves from Rough Surfaces", (Pergamon, New York, 1963)
- (253) G. T. Ruck, D. E. Barrick, W. D. Stuart and C. K. Krickbaum, "Radar Cross Section Handbook", (Plenum, New York, Vol. 2, Chap. 9, (1970).
- (254) N. George, A. Jain, Appl. Phys. 4, 201 (1974).
- (255) N. George, A. Jain, and R. D. Melville, Jr., Appl. Phys. 6, 65 (1975).
- (256) "Handbook of Lasers", ed. R. J. Pressley, The Chemical Rubber Co. (1971).
- (257) "Laser Focus: 1976 Buyer's Guide", Adv. Technology Publ., Inc., Newton, Mass. (February 1976).
- (258) R. A. Brandewic and W. C. Davis, "Parametric Study of a 10.6- μ m Laser Radar", Appl. Opt. 11, 1526 (1972).
- (259) H. Koschmieder, Beitr. Phys. Atmos. 12, 33, 171 (1924)

- (260) R. J. Charlson, N. C. Ahlquist, H. Selvidge, and P. B. MacCready, Jr., "Monitoring of Atmospheric Aerosol Parameters with the Integrating Nephelometer," *J. Air Poll. Control Assoc.* 19, 937 (1969).
- (261) W. Fett, *Beitr. Phys. Atmos.* 40, 262 (1967).
- (262) J. S. Curcio, G. L. Knestrick, and T. H. Cosden, "Atmospheric Scattering in the Visible and Infrared," *NRL Rep.* 5567, Washington, D. C. (1961).
- (263) L. Elterman, "Relationship Between Vertical Attenuation and Surface Meteorological Range," *Appl. Optics* 9, 1804 (1970).
- (263a) L. Elterman, "UV, Visible and IR Attenuation for Altitudes to 50 km, 1968," *AFCRL-68-0153* (Apr. 1968).
- (264) M. P. McCormick and W. H. Fuller, Jr., "Lidar Applications to Pollution Studies," *AIAA Paper No. 71-1056*, Joint Conf. Sens. Environm. Pollutants, Palo Alto, CA (Nov. 1971).
- (265) J. A. Curcio, L. F. Drummeter and T. H. Cosden, "The Absorption Spectrum of the Atmosphere from 4400 to 5500 Å," *NRL Report* 4669 (9Dec1955) (AD81133).
- (266) J. A. Curcio and G. L. Knestrick, "An Atlas of the Absorption of the Atmosphere from 5400 to 8520 Å," *NRL Report* 4601 (23Aug1955) (AD71520).
- (267) C. B. Ludwig, W. Malkmus, J. E. Reardon and J. A. L. Thomson, Handbook of Infrared Radiation from Combustion Gases, NASA SP-3080 (1973).
- (268) R. J. Bell, Introductory Fourier Transform Spectroscopy, Academic Press, New York, 1972.
- (269) C. E. Dunning and Fred E. Nicodemus, "Targets," Handbook of Military Infrared Technology, p. 57, Office of Naval Research (1965).
- (270) C. B. Ludwig, M. Griggs, W. Malkmus and E. R. Bartle, "Air Pollution Measurements from Satellites," *NASA CR-2324* (1973).
- (271) M. Griggs, C. G. Ludwig, and M. L. Streiff, *Proc. 2nd Int. Clean Air Congress*, p 500, Ed. M. M. England and W. T. Beary, Academic Press, N. Y., 1971.
- (272) *Phys. Zeitschrift*, 1, 289 (1900).
- (273) Wolfe, Wm. L., Ed. Handbook of Military Infrared Technology. Office of Naval Research, p. 48 (1965).

References (274) through (288) are not assigned

- (289) 41FR37660, September 7, 1976.
- (290) D. T. Williams and R. N. Hager, Jr., "The Derivative Spectrometer", *Applied Optics* 9, 1597 (1970).
- (291) J. B. Clements, EPA, Research Triangle Park, North Carolina, phone: (919)541-2196, personal communication.
- (292) H. Segal, "Monitoring Concorde Emissions", *J. Air Poll. Contr. Assn.*, 27, 623, (1977).
- (293) Private Communications, Mr. John Thompkins, FAA, Airways Facility, San Diego, CA (March, 1976).
- (294) J. Reid, B. K. Garside, J. Shewchun, M. El-Sherbiny and E. A. Ballik, "High Sensitivity Point Monitoring of Atmospheric Gases Employing Tunable Diode Lasers," *Applied Optics*, being published.
- (295) *Pollution Equipment News*, Vol. 10, No. 3, page 46 (June 1977).
- (296) C. D. Hollowell and R. D. McLaughlin, "Instrumentation for Air Pollution Monitoring *Environ. Sci. Techn.* f, 1011 (1973).
- (297) "Instrument and Techniques for Exhaust Gas Emissions Measurement", SAE Recommended Practice, J254 (1971).
- (298) "Nondispersive Infrared Analyzer for Specific Gases in Complex Mixtures", NASA TECH BRIEF, Ames Research Center (May 1972).
- (299) Elfers, L. A. Field Operations Guide for Automatic Air Monitoring Equipment, NTIS Report PB 204650, (July 1971).
- (300) Evans, R., EPA-Las Vegas, private communication, 1975.

REFERENCES

- (301) G. A. Briggs, "Plume Rise," Air Resources Atmospheric Turbulence and Diffusion Laboratory, Environmental Science Services Administration, Oak Ridge, Tennessee, 1969.
- (302) G. A. Briggs, "Plume Rise: A Recent Critical Review," Nuclear Safety, Vol. 12 (No. 1), January-February, 1971, pp. 15-24.
- (303) F. Pasquill, "Atmospheric Diffusion," D. Van Nostrand, New York, 1972.
- (304) O. G. Sutton, "Micrometeorology," McGraw-Hill, New York, 1953.
- (305) D. B. Turner, "Workbook on Atmospheric Dispersion Estimates," U. S. Department of Health, Education, and Welfare, U. S. Public Health Service, Report No. 999-AP-26.
- (306) E. M. Darling, Jr., "Computer Modeling of Transportation-Generated Air Pollution: A State-of-the-Art Survey," U. S. Department of Transportation, Report No. DOT-TSC-OST-72-20, June 1972.
- (307) M. Smith (Editor), "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents," Am. Soc. of Mech. Eng., 1968.
- (308) D. B. Turner, "A Diffusion Model of an Urban Area," Journal of Applied Meteorology, Vol. 3, February 1964, pp. 83-91.
- (309) F. Pasquill, "The Estimation of the Dispersion of Windborne Material," Meteorology Magazine, Vol. 90, 1961, pp. 33-49.
- (310) F. A. Gifford, Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," Nuclear Safety, Vol. 4 (No. 2), July-August 1961, pp. 47-51.
- (311) J. J. Roberts, E. J. Crolse, A. S. Kennedy, J. E. Norco and L. A. Conley, "A Multiple-Source Urban Atmospheric Dispersion Model," Argonne National Laboratory, Report No. ANL/ES-CC-007, May 1970.

- (312) D. M. Rote and L. E. Wangen, "A Generalized Air Quality Assessment Model for Air Force Operations," Air Force Weapons Laboratory, Report No. AFWL-TR-74-304, February 1975.
- (313) D. G. Martin and J. A. Tikvart, "A General Atmospheric Diffusion Model for Estimating the Effects on Air Quality of One or More Sources," Air Pollution Control Association paper, June 1968, pp. 68-148.
- (314) "Air Quality Display Model," TRW Systems, November 1969, NTIS No. PB-189194.
- (315) R. C. Sklarew, A. J. Fabrick, and J. E. Prager, "A Particle-in-Cell Method for Numerical Solution of the Atmospheric Diffusion Equation and Applications to Air Pollution Problems," Systems, Science & Software, Report 3SR-844, Volume 1, November 1971.
- (316) K. L. Calder, "On the Equation of Atmospheric Diffusion," Quarterly J. Royal Meteorological Society, Volume 91, 1965, pp. 514.
- (317) J. M. Haber, "A Survey of Computer Models for Predicting Air Pollution from Airports," J. H. Wiggins Company, Report No. 75-1231-1, May 23, 1975.
- (318) G. C. Holyworth, "Estimates of Mean Maximum Mixing Depths in the Contiguous United States," Monthly Weather Review, Volume 92 (No. 5), May 1964, pp. 235-242.
- (319) J. Z. Holland, "A Meteorological Survey of the Oak Ridge Area," Atomic Energy Commission, Report No. ORO-99, Washington, D. C., 1953, pp. 554-559.
- (320) R. I. Larsen, "A New Mathematical Model of Air Pollution Concentration Averaging Time and Frequency," Journal of the Air Pollution Control Association, Volume 19 (No. 1), January 1969.
- (321) M. Platt, et. al., "The Potential Impact of Aircraft Emissions upon Air Quality," Northern Research and Engineering Corporation, Report No. 1167-1, December 1971.

- (322) M. Platt, et. al., "Assessing the Impact of Aircraft Emissions Upon Air Quality," presented at the 65th Annual Meeting of the Air Pollution Control Association, Miami Beach, Florida, June 18-22, 1972.
- (323) M. Platt and E. K. Bastress, "The Impact of Aircraft Emissions Upon Air Quality," presented at the International Conference on Transportation and the Environment (No. 720610).
- (324) D. O. Martin, "An Urban Diffusion Model for Estimating Long-Term Average Values of Air Quality," Journal of the Air Pollution Control Association, Volume 21 (No. 1), January 1971, pp. 16-19.
- (325) "Nature and Control of Aircraft Engine Exhaust Emissions," Northern Research and Engineering Corporation, Report. No. 1134-1, Cambridge, Massachusetts, November 1968.
- (326) S. D. Thayer, "Impact on the Proposed Expansion of the Salt Lake City International Airport on Air Quality," GEOMET Report No. EF-306, March 29, 1974.
- (327) S. D. Thayer, et. al., "Model Verification-Aircraft Emission Impact on Air Quality," GEOMET Report No. EF-262, May 1974.
- (328) S. D. Thayer, "The Development and Validation of an Airport Air Quality Model," Preprint from the Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, California, September 9-13, 1974.
- (329) J. E. Norco, et. al., "An Air Pollution Impact Methodology for Airports - Phase I," Argonne National Laboratory, January 1973, NTIS PB-220-987.
- (330) D. M. Rote, et. al., "Airport Vicinity Air Pollution Study," Federal Aviation Administration, Report No. FAA-RR-73-113, December 1973.
- (331) D. M. Rote, et. al., "Airport Vicinity Air Pollution Study - Model Application and Validation and Air Quality Impact Analysis at Washington National Airport," Federal Aviation Administration Report No. FAA-RD-74-132, July 1974.

- (332) R. R. Cirello, et. al., "Airport Vicinity Air Pollution Study: The Impact of Modified Aircraft Taxi Procedures on Airport Air Quality," Federal Aviation Administration Report No. FAA-RD-212, December 1974.
- (333) J. E. Carson and H. Moses, "The Validity of Currently Popular Plume Rise Formulas," in Proceedings USAEC Meteorological Information Meeting, held at Chalk River Nuclear Laboratories, September 11-14, 1967, pp. 1-20.
- (334) I. T. Wang and R. M. Rote, "A Finite Line Source Dispersion Model for Mobile Source Air Pollution," Journal of the Air Pollution Control Association, Volume 25 (No. 7), July 1975, pp. 730-733.
- (335) T. D. Wolsko, M. T. Matthies, and R. E. Wendell, "Transportation Air Pollutant Emissions Handbook," Argonne National Laboratory, Report No. ANL/ES-15, Argonne, Illinois, July 1972.
- (336) D. M. Rote and L. E. Wangen, "A Generalized Air Quality Assessment Model for Air Force Operations," U. S. Air Force Weapons Laboratory, Report No. AFWL-TR-74-304, February 1975.
- (337) "Development of Procedures to Simulate Motor Vehicle Pollution Levels," ERT Document P-343-F, Environmental Research and Technology, Inc., Lexington, Massachusetts.
- (338) B. A. Egan and J. R. Mahoney, "Numerical Modeling of Advection and Diffusion of Urban Area Source Pollutants," J. Applied Meteorology, 1972, pp. 312-332.
- (339) P. B. S. Lissaman, "A Simple Unsteady Concentration Model Explicitly Incorporating Ground Roughness and Heat Flux," APCA Paper 73-219, presented at 66th APCA Meeting, Chicago, Illinois, June 1973.
- (340) P. M. Roth, et. al., "An Examination of the Accuracy and Adequacy of Air Quality and Monitoring Data for Use in Assessing the Impact of EPA Significant Deterioration Regulations on Energy Development," Contract EF 75-58R for American Petroleum Institute, August 1975.

APPENDICES

- I (40 CFR 50) National Primary and Secondary Ambient Air Quality Standards
- II (40 CFR 53) Ambient Air Monitoring Reference and Equivalent Methods
- III Guideline For Public Reporting of Daily Air Quality
- IV (40 CFR 87) Control of Air Pollution From Aircraft and Aircraft Engines
- V Review of Calibration Span Gases
- VI List of Commercially Available Point Samplers
- VII Derivation of Signal-To-Noise Ratio Equations and Error Analysis
- VIII Meteorological Instruments For Use in The Calibration Test Range
- IX Electromagnetic Interference Characteristics Requirements for Equipment

APPENDIX I

NATIONAL PRIMARY AND SECONDARY
AMBIENT AIR QUALITY STANDARDS
(40 C FR 50)

CHAPTER I—ENVIRONMENTAL PROTECTION AGENCY (Continued)

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SUBCHAPTER C—AIR PROGRAMS

50.1	Definitions.
50.2	As used in this part, all terms not defined herein shall have the meaning given them by the Act.
50.3	"Act" means the Clean Air Act, as amended (42 U.S.C. 1857-1857i, as amended by Pub. L. 91-604).
50.4	"Agency" means the Environmental Protection Agency.
50.5	"Administrator" means the Administrator of the Environmental Protection Agency.
50.6	"Ambient air" means that portion of the atmosphere, external to buildings, to which the general public has access.
50.7	"Reference method" means a method of sampling and analyzing the ambient air for an air pollutant that is specified as a reference method in an appendix to this part, or a method that has been designated as a reference method in accordance with Part 53 of this chapter; it does not include a method for which a reference method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.
50.8	"Equivalent method" means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with Part 53 of this chapter; it does not include a method for which an equivalent method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.
50.9	36 FR 22384, Nov. 25, 1971, as amended at 41 FR 11253, Mar. 17, 1976
50.10	Scope.
50.11	(a) National primary and secondary ambient air quality standards under section 109 of the Act are set forth in this part.
50.12	(b) National primary ambient air quality standards define levels of air quality which the Administrator judges are necessary, with an adequate margin of safety, to protect the public health, National secondary ambient air quality standards define levels of air quality which the Administrator judges necessary to protect the public welfare from any known or anticipated adverse effects of a pollutant. Such standards are subject to revision, and additional primary and secondary standards may be promulgated as the Administrator deems necessary.

§ 50.1 Title 40—Protection of Environment

§ 50.1 Definitions.

- (a) As used in this part, all terms not defined herein shall have the meaning given them by the Act.
- (b) "Act" means the Clean Air Act, as amended (42 U.S.C. 1857-1857i, as amended by Pub. L. 91-604).
- (c) "Agency" means the Environmental Protection Agency.
- (d) "Administrator" means the Administrator of the Environmental Protection Agency.
- (e) "Ambient air" means that portion of the atmosphere, external to buildings, to which the general public has access.
- (f) "Reference method" means a method of sampling and analyzing the ambient air for an air pollutant that is specified as a reference method in an appendix to this part, or a method that has been designated as a reference method in accordance with Part 53 of this chapter; it does not include a method for which a reference method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.
- (g) "Equivalent method" means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with Part 53 of this chapter; it does not include a method for which an equivalent method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.

- (h) "National primary ambient air quality standards for sulfur oxides (sulfur dioxide)." means the national primary ambient air quality standards for sulfur oxides measured as sulfur dioxide by the reference method described in Appendix A to this part, or by an equivalent method, are:
- (i) 80 micrograms per cubic meter (0.03 p.p.m.)—annual arithmetic mean.
- (j) 365 micrograms per cubic meter (0.14 p.p.m.)—Maximum 24-hour concentration not to be exceeded more than once per year.
- (k) National secondary ambient air quality standards for sulfur oxides (sulfur dioxide).

§ 50.3 Reference conditions.

All measurements of air quality are corrected to a reference temperature of 25° C. and to a reference pressure of 760 millimeters of mercury (1,013.2 millibars).

§ 50.4 National primary ambient air quality standards for sulfur oxides (sulfur dioxide).

The national primary ambient air quality standards for sulfur oxides measured as sulfur dioxide by the reference method described in Appendix A to this part, or by an equivalent method, are:

- (a) 80 micrograms per cubic meter (0.03 p.p.m.)—annual arithmetic mean.
- (b) 365 micrograms per cubic meter (0.14 p.p.m.)—Maximum 24-hour concentration not to be exceeded more than once per year.

§ 50.5 National secondary ambient air quality standards for sulfur oxides (sulfur dioxide).

The national secondary ambient air quality standard for sulfur dioxide measured as sulfur dioxide by the reference method described in Appendix A to this part, or by any equivalent method is 1,300 micrograms per cubic meter (0.5 p.p.m.) maximum 3-hour concentration not to be exceeded more than once per year.

[38 FR 26581, Sept. 14, 1973]

§ 50.6 National primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter, measured by the reference method de-

scribed in Appendix B to this part, or by an equivalent method, are:

(a) 75 micrograms per cubic meter—annual geometric mean.

(b) 260 micrograms per cubic meter—maximum 24-hour concentration not to be exceeded more than once per year.

§ 50.7 National secondary ambient air quality standards for particulate matter.

The national secondary ambient air quality standards for particulate matter, measured by the reference method described in Appendix B to this part, or by an equivalent method, are:

(a) 60 micrograms per cubic meter—annual geometric mean, as a guide to be used in assessing implementation plans to achieve the 24-hour standard.

(b) 150 micrograms per cubic meter—maximum 24-hour concentration not to be exceeded more than once per year.

§ 50.8 National primary and secondary ambient air quality standards for carbon monoxide.

The national primary and secondary ambient air quality standards for carbon monoxide, measured by a reference method based on Appendix C to this part and designated in accordance with Part 53 of this chapter, or by an equivalent method, are:

(a) 10 milligrams per cubic meter (9 p.p.m.)—maximum 8-hour concentration not to be exceeded more than once per year.

(b) 40 milligrams per cubic meter (35 p.p.m.)—maximum 1-hour concentration not to be exceeded more than once per year.

[36 FR 22284, Nov. 25, 1971, as amended at 40 FR 7043, Feb. 18, 1975]

§ 50.9 National primary and secondary ambient air quality standards for photochemical oxidants.

The national primary and secondary ambient air quality standard for photochemical oxidants, measured and corrected for interferences due to nitrogen oxides and sulfur dioxide by a reference method based on Appendix D to this part and designated in accordance with Part 53 of this chapter, or by an equivalent method, is: 160 micrograms per cubic meter (0.08 p.p.m.) maximum 1-hour concentration not to be exceeded more than once per year.

[40 FR 7043, Feb. 18, 1975]

§ 50.10 National primary and secondary ambient air quality standards for hydrocarbons.

The hydrocarbons standard is for use as a guide in devising implementation plans to achieve oxidant standards. The national primary and secondary ambient air quality standard for hydrocarbons, measured and corrected for methane by the reference method described in Appendix E to this part, or by an equivalent method, is: 160 micrograms per cubic meter (0.24 p.p.m.)—maximum 3-hour concentration (8 to 9 a.m.) not to be exceeded more than once per year.

§ 50.11 National primary and secondary ambient air quality standard for nitrogen dioxide.

The national primary and secondary ambient air quality standard for nitrogen dioxide, measured by the reference method described in Appendix F to this part, or by an equivalent method, is: 100 micrograms per cubic meter (0.05 p.p.m.)—annual arithmetic mean.

APPENDIX A—REFERENCE METHOD FOR THE DETERMINATION OF SULFUR DIOXIDE IN THE AMBIENT AIR (PARAOSANILINE METHOD)

1. Principle and Applicability. 1.1 Sulfur dioxide is absorbed from air in a solution of potassium tetrachloromercurate (TCM). A dichlorosulfite-mercuric complex, which results oxidation by the oxygen in the air, is formed (1, 2). Once formed, this complex is stable to strong oxidants (e.g., ozone, oxides of nitrogen). The complex is reacted with paraosanine and formaldehyde to form intensely colored paraosanine methyl sulfonate acid (3). The absorbance of the solution is measured photometrically at 540 mμ. The method is applicable to the measurement of sulfur dioxide in ambient air using sampling periods up to 24 hours.

2. Range and Sensitivity. 2.1 Concentrations of sulfur dioxide in the range of 25 to 1,050 μg/m³ (0.01 to 0.40 p.p.m.) can be measured under the conditions given. One can measure concentrations below 25 μg/m³ by sampling larger volumes of air, but only if the absorption efficiency of the particular system is first determined. Higher concentrations can be analyzed by using smaller gas samples, a larger collection volume, or a suitable aliquot of the collected sample. Beer's Law is followed through the working range from 0.03 to 1.0 absorbance units (0.3 to 20 μg of sulfur dioxide in 25 ml. final solution concentration).

2.2 The lower limit of detection of sulfur dioxide in 10 ml. TCM is 0.73 μg (based on twice the standard deviation) representing a concentration of 25 μg/m³ (0.01 p.p.m.) in an air sample of 30 liters.

3. Interferences. 3.1 The effects of the principal known interferences have been minimized or eliminated. Interferences by oxides of nitrogen are eliminated by sulfamic acid (4, 5), ozone by time-delay (6), and heavy metals by EDTA (ethylenediaminetetraacetic acid, disodium salt) and phosphoric acid (4, 6). At least 80 μg. Fe (III), 10 μg. Mn (II), and 10 μg. Cr (III) in 10 ml. absorbing reagent can be tolerated in the procedure. No significant interference was found with 10 μg. Cu (II) and 22 μg. V (V).

4. Precision, Accuracy, and Stability. 4.1 Relative standard deviation at the 95 percent confidence level for 100 samples of typical ambient air using standard samples (5) is 1.5 percent.

4.2 After sample collection the solutions are relatively stable at 22° C. losses of sulfur dioxide occur at the rate of 1 percent per day. When samples are stored at 6° C. for 30 days, no detectable losses of sulfur dioxide occur. The presence of EDTA enhances the stability of SO₂ in solution, and the rate of decay is independent of the concentration of SO₂ (7).

5. Apparatus.

5.1 Sampling.

5.1.1 Absorber. Absorbers normally used in air pollution sampling are acceptable for concentrations above 25 μg./m³ (0.01 p.p.m.). An all-glass midgey impinger, as shown in Figure A1, is recommended for 30-minute and 1-hour sampling.

5.1.2 For 24-hour sampling, assemble an absorber from the following parts: Polypropylene 2-port tube closures, special manufacture (available from Bel-Art Products, Pequannock, N.J.). Glass impingers, 6 mm. tubing, 6 inches long, one end drawn to small diameter such that No. 79 jewelers drill will pass through, but No. 78 jewelers drill will not. (Other end fire-polished.)

Polypropylene tubes, 164 by 32 mm. (Nalgene or equal).

5.1.3 Pump. Capable of maintaining an air pressure differential greater than 0.7 atmosphere.

5.1.4 Flowmeter. Critical orifice.

A calibrated rotameter or critical orifice capable of measuring air flow within +2 percent. For 30-minute sampling, a 22-gauge hypodermic needle 1 inch long may be used as a critical orifice to give a flow of about 1 liter/minute. For 1-hour sampling, a 23-gauge hypodermic needle five-eighths of an inch long may be used as a critical orifice to give a flow of about 0.6 liter/minute. For 24-hour sampling, a 27-gauge hypodermic needle three-fifths of an inch long may be used to give a flow of about 0.2 liter/minute. Use a membrane filter to protect the needle (Fisher Scientific).

5.2 Spectrophotometer. Suitable for measurement of absorbance at 540 nm. with an effective spectral band width of less than

15 nm. Reagent blank problems may occur with spectrophotometers having greater spectral band width. The wavelength calibration of the instrument should be verified. If transmittance is measured, this can be converted to absorbance:

$$A = \log_{10} (1/T)$$

6. Reagents.

6.1 Sampling.

6.1.1 Distilled water. Must be free from oxidants.

6.1.2 Absorbing Reagent 10.04 M Potassium Tetrachloromercurate (TCM). Dissolve 10.99 g. mercuric chloride, 0.004 g. EDTA (ethylenediaminetetraacetic acid, disodium salt), and 6.0 g. potassium chloride in water and bring to mark in a 1,000-ml. volumetric flask. (Caution: highly poisonous. If spilled on skin, flush off with water immediately). The pH of this reagent should be approximately 4.0, but it has been shown that there is no appreciable difference in collection efficiency over the range of pH 5 to pH 3.17. The absorbing reagent is normally stable for 6 months. If a precipitate forms, discard the reagent.

6.2 Analysis.

6.2.1 Sulfuric Acid (0.5 percent). Dissolve 0.5 g. sulfuric acid in 100 ml. distilled water. Prepare freshly.

6.2.2 Formaldehyde (0.2 percent). Dilute 5 ml. formaldehyde solution (36-38 percent) to 1,000 ml. with distilled water. Prepare daily.

6.2.3 Stock Iodine Solution (0.1 N). Place 12.7 g. iodine in a 250-ml. beaker; add 40 g. potassium iodide and 25 ml. water. Stir until all is dissolved, then dilute to 1,000 ml. with distilled water.

6.2.4 Iodine Solution (0.01 N). Prepare approximately 0.01 N iodine solution by diluting 80 ml. of stock solution to 800 ml. with distilled water.

6.2.5 Starch Indicator Solution. Titrate 0.002 g. soluble starch and 0.002 g. mercuric iodide (Fisher Scientific) with a little water, and add the paste slowly to 200 ml. distilled water. Continue boiling until the solution is clear; cool, and transfer to a glass-stoppered bottle.

6.2.6 Stock Sodium Thiosulfate Solution (0.1 N). Prepare a stock solution by dissolving 25 g. sodium thiosulfate (Na₂S₂O₃·5H₂O) in 1,000 ml. freshly boiled, cooled, distilled water and add 0.1 g. sodium carbonate to the solution. Allow the solution to stand 1 day before standardizing. To standardize, accurately weigh, to the nearest 0.1 mg., 1.6 g. primary standard potassium iodate dried at 180° C. and dilute to volume in a 500-ml. volumetric flask. To a 500-ml. iodine flask, pipet 50 ml. of iodine solution. Add 2 g. potassium iodide and 10 ml. of 1 N hydrochloric acid. Stopper the flask. After 5 minutes, titrate with stock thiosulfate solution to a pale yellow. Add 5 ml. starch indicator solution and continue the titration until the blue color disappears.

Calculate the normality of the stock N=Normality of stock thiosulfate solution.

$$N = \frac{W}{M} \times 2.80$$

W = Volume of stock thiosulfate required, ml.
M = Weight of potassium iodate, grams.

$$2.80 = \frac{10^6 (\text{conc. soln of g. to mg.}) \times 0.1 (\text{fraction iodate used})}{35.87 (\text{equivalent weight of potassium iodate})}$$

6.2.7 Sodium Thiosulfate Titrant (0.01 N). Dilute 100 ml. of the stock thiosulfate solution to 1,000 ml. with freshly boiled distilled water.

Normality = Normality of stock solution $\times 0.100$.

6.2.8 Standardized Sulfite Solution for Preparation of Working Sulfite-TCM Solution. Dissolve 0.3 g. sodium metabisulfite ($\text{Na}_2\text{S}_2\text{O}_3$) or 0.40 g. sodium sulfite (Na_2SO_3) in 800 ml. of recently boiled, cooled distilled water. Sulfite solutions are unstable in the presence of oxygen and must be kept in the dark to prevent this instability. This solution contains the equivalent of 320 to 400 $\mu\text{g.}/\text{ml.}$ of SO_2 . The actual concentration of the solution is determined by adding excess iodine and back-titrating with standard sodium thiosulfate solution. To back-titrate, pipet 50 ml. of the 0.01 N iodine into each of two 600-ml. iodine flasks (A and B). To flask B (sample) pipet 25 ml. sulfite solution. Stopper the flasks and allow to react for 5 minutes. Prepare the working sulfite-TCM solution by adding 25 ml. of the 0.01 N thiosulfate titrate each flask in turn to a pale yellow. Then add 5 ml. starch solution and continue the titration until the blue color disappears.

6.2.9 Working Sulfite-TCM Solution. Pipet accurately 2 ml. of the standard solution into a 100 ml. volumetric flask and bring to mark with 0.04 M TCM. Calculate the concentration of sulfur dioxide in the working solution:

$$\mu\text{g. SO}_2/\text{ml.} = (A - B) (N) (32,000) \times 0.02$$

A = Volume thiosulfate for blank, ml.
B = Volume thiosulfate for sample, ml.
N = Normality of thiosulfate titrant.

32,000 = Milliequivalent wt. of SO_2 , $\mu\text{g.}$
25 = Volume standard sulfite solution, ml.
0.02 = Dilution factor.

This solution is stable for 30 days if kept at 8°C. (refrigerator). If not kept at 8°C. , prepare daily.

6.2.10 Purified Paracresolamine Stock Solution (0.2 Percent Normality). The paracresolamine dye must meet the following performance specifications: (1) the dye must

be sampled by multiplying the flow rate by the time in minutes and record the atmospheric pressure and temperature. Remove and stopper the impinger. If the sample must be stored for more than a day before analysis, keep it at 5°C. in a refrigerator (see 4.3).

7.1.3 24-Hour Sampling. Place 50 ml. TCM solution in the impinger and collect sample at 0.2 liter/minute for 24 hours from midnight to midnight. Make sure no entrainment of solution results with the impinger. During collection and storage protect from direct sunlight. Determine the total air volume by multiplying the air flow rate by the time in minutes. The correction for 24-hour measurements for temperature and pressure is extremely difficult and is not ordinarily done. However, the accuracy of the measurement will be improved if meaningful corrections can be applied. If storage is necessary, refrigerate at 5°C. (see 4.2).

7.2 Analysis, Preparation, After collection.
7.2.1 Sample Preparation. After collection, if a precipitate is observed in the sample, centrifuge.

7.2.1.1 30-Minute and 1-Hour Samples. Transfer the sample quantitatively to a 25-ml. volumetric flask; use about 5 ml. distilled water for rinsing. Delay analyses for 20 minutes to allow any ozone to decompose.

7.2.1.2 24-Hour Sample. Dilute the entire sample to 50 ml. with absorbing solution. Pipet 5 ml. of the sample into a 25-ml. volumetric flask for chemical analysis. Bring volume to 10 ml. with absorbing reagent. Delay analyses for 20 minutes to allow any ozone to decompose.

7.2.2 Determination. For each set of determinations prepare a reagent blank by adding 10 ml. unspiked TCM solution to a 25-ml. volumetric flask. Pipet 5 ml. of the unspiked TCM solution into a 25-ml. volumetric flask. To each flask containing either sample, control solution, or reagent blank, add 1 ml. 0.6 percent sulfamic acid and allow to react 10 minutes to destroy the nitrite from oxides of nitrogen. Accurately pipet in 2 ml. 0.2 percent formaldehyde solution, then 5 ml. paracresolamine solution. Start a laboratory timer that has been set for 30 minutes. Bring all flasks to volume with freshly boiled and cooled distilled water and mix thoroughly. After 30 minutes and before 60 minutes, determine the absorbance of the sample (denote as A), reagent blank (denote as A₀) and control solution at 545 nm. using 1-cm. optical path length cell. Use distilled water, not the reagent blank, as the reference. (Note: This is important because of the color change which can be induced in the cell compartment of a spectrophotometer.) Do not allow the colored solution to stand

in the absorbance cell, because a film of dye may be deposited. Clean cells with alcohol after use. If the temperature of the determinations does not differ by more than 1°C. from the calibration temperature (6.2), the reagent blank should be obtained 0.03 absorbance units of the y-intercept of the calibration curve (6.2). If the reagent blank differs by more than 0.03 absorbance unit from that found in the calibration curve, prepare a new curve.

7.2.3 Absorbance Range. If the absorbance of the sample solution ranges between 1.0 and 2.0, the sample can be diluted 1:1 with a portion of the reagent blank and read within a few minutes. Solutions with higher absorbance can be diluted up to sixfold with the reagent blank in order to obtain accurate readings within 10 percent of the true absorbance value.

8. Calibration and Efficiency.
8.1 Flowmeters and Hypodermic Needles. Calibrate flowmeters and hypodermic needles (8.1.1) and calibrated wet test meter.

8.2 Calibration Curve.
8.2.1 Procedure with Sulfite Solution. Accurately pipet graduated amounts of the working sulfite-TCM solution (6.2.9) (such as 0, 0.5, 1, 2, 3, and 4 ml.) into a series of 25-ml. volumetric flasks. Add sufficient TCM solution to each flask to bring the volume to approximately 10 ml. Then add the remaining reagent as described in 7.2.2. For maximum precision use a constant-temperature bath. The temperature of calibration must be maintained within $\pm 1^\circ\text{C.}$ and in the range of 20° to 30°C. The temperature of calibration and the temperature of analysis must be within 2°C. Plot the absorbance against the total concentration in $\mu\text{g. SO}_2/\text{ml.}$ of the corresponding solution. The calibration curve is standard (Section 6.2.4) in $\mu\text{g. SO}_2/\text{ml.}$ times the ml. sulfite solution added (ref. $\text{SO}_2 = \mu\text{g.}/\text{ml. SO}_2 \times \text{ml. added}$). A linear relationship should be obtained, and the y-intercept should be within 0.03 absorbance unit of the zero standard absorbance. For maximum precision determine the line of best fit using regression analysis by the method of least squares. Determine the slope of the line of best fit, calculate its reciprocal and denote as B. B is the calibration factor. (See Section 6.2.10.1 for specifications on the slope of the calibration curve). This calibration factor is used for calculating the concentration provided there are no radical changes in temperature or pH. At least one control sample containing a known concentration of SO_2 for each series of determinations is recommended to insure the reliability of this factor.

8.2.2 Procedure with SO_2 Permeation Tubes.
8.2.2.1 General Considerations. Atmospheres containing accurately known amounts of sulfur dioxide at levels of interest can be

prepared using permeation tubes. In the systems for generating these atmospheres, the permeation tube emits SO_2 gas at a known, low, constant rate, provided the temperature of the tube is held constant ($\pm 0.1^\circ\text{C}$). The flow rate of the gas is determined directly as a function of the temperature of the tube. The SO_2 gas permeating from the tube is carried by a low flow of inert gas to a mixing chamber where it is accurately diluted with SO_2 -free air to the level of interest and the sample taken. These systems are shown schematically in Figures A2 and A3 and have been described in detail by O'Keefe and Orman (9), Scarfingelli, Frey, and Saltzman (10), and Scarfingelli, O'Keefe, Rosenber, and Bell (11).

8.2.2.3 Preparation of Standard Atmospheres. Permeation tubes may be prepared or purchased. Scarfingelli, O'Keefe, Rosenber, and Bell (11) give detailed, explicit directions for permeation tube preparation. The flow rate of the gas is determined by a variable flow from the National Bureau of Standards. Tube permeation rates from 0.2 to 0.4 $\mu\text{g}/\text{min}$, inert gas flows of about 50 ml/min, and dilution air flow rates from 1.1 to 15 liters/minute conveniently give standard atmospheres containing desired levels of SO_2 (25 to 390 $\mu\text{g}/\text{m}^3$; 0.01 to 0.15 p.p.m.). The concentration of SO_2 in any standard atmosphere can be calculated as follows:

$$C = \frac{P \times 10^3}{B_1 + B_2}$$

Where:

C = Concentration of SO_2 , $\mu\text{g}/\text{m}^3$ at reference conditions.
 P = Tube permeation rate, $\mu\text{g}/\text{min}$.
 B_1 = Flow rate of dilution air, liter/minute at reference conditions.
 B_2 = Flow rate of inert gas, liter/minute at reference conditions.

8.2.2.3 Sampling and Preparation of Calibration Curve. Prepare a series (usually six) of standard atmospheres containing SO_2 levels from 25 to 390 $\mu\text{g}/\text{m}^3$. Sample each atmosphere using similar apparatus and taking exactly the same air volume as will be done in atmospheric sampling. Determine absorbances as directed in 7.2. Plot the concentration of SO_2 in $\mu\text{g}/\text{m}^3$ (x-axis) against $A - A_0$ values (y-axis), draw the straight line of best fit and determine the slope. Alternatively, regression analysis by the method of least squares may be used to calculate the slope. Calculate the reciprocal of the slope and denote it as B .

8.3 Sampling Efficiency. Collection efficiency is above 99 percent; efficiency may fall off, however, at concentrations below 25 $\mu\text{g}/\text{m}^3$ (12, 13).

9. Calculations.

9.1 Conversion of Volume. Convert the volume of air sampled to the volume at reference conditions of 25°C and 760 mm. Hg.

(On 24-hour samples, this may not be possible.)

$$V_a = V \times \frac{P}{760} \times \frac{273}{1 + 273}$$

V_a = Volume of air at 25°C and 760 mm. Hg. item.

V = Volume of air sampled, liter.

P = Barometric pressure, mm. Hg.

t = Temperature of air sample, $^\circ\text{C}$.

9.2 Sulfur Dioxide Concentration.
 9.2.1 When endite solutions are used to prepare calibration curves, compute the concentration of sulfur dioxide in the sample:

$$\mu\text{g SO}_2/\text{m}^3 = \frac{(A - A_0) (10^3) (B_1) \times D}{V_a}$$

A = Sample absorbance.

A_0 = Reagent blank absorbance.

10^3 = Conversion of liters to cubic meters.

V_a = The sample corrected to 25°C and 760 mm. Hg. item.

B_1 = Calibration factor, $\mu\text{g}/\text{absorbance}$ unit.

D = Dilution factor.

For 30-minute and 1-hour samples, $D = 1$.

For 24-hour samples, $D = 10$.

9.2.2 When SO_2 gas standard atmospheres are used to prepare calibration curves, compute the sulfur dioxide in the sample by the following formula:

$$\text{SO}_2, \mu\text{g}/\text{m}^3 = (A - A_0) \times B_1$$

A = Sample absorbance.

A_0 = Reagent blank absorbance.

B_1 = (See 8.2.2.3).

9.2.3 Conversion of $\mu\text{g}/\text{m}^3$ to p.p.m. = If desired, the concentration of sulfur dioxide may be calculated as p.p.m. SO_2 at reference conditions as follows:

$$\text{p.p.m. SO}_2 = \mu\text{g SO}_2/\text{m}^3 \times 3.82 \times 10^{-4}$$

10. References.

- (1) West, P. W., and Oake, O. C., "Fixation of Sulfur Dioxide as Sulfonamides and Subsequent Colorimetric Determination", *Anal. Chem.* 38, 1818 (1966).
- (2) Ehrhardt, P., "Inorganic Chemistry," 2nd Edition, Edited by P. C. I. Thorne and E. R. Roberia, 5th Edition, Interscience, (1948).
- (3) Lytle, G. R., Dowling, P. B., and Blanchard, V. J., "Quantitative Determination of Formaldehyde in Parts Per Hundred Million Concentration Levels", *J. Air Poll. Cont. Assoc.* 15, 106 (1965).
- (4) Scarfingelli, P. F., Saltzman, B. E., and Frey, S. A., "Spectrophotometric Determination of Atmospheric Sulfur Dioxide", *Anal. Chem.* 39, 1709 (1967).

- (5) Pata, J. E., Ammons, B. E., Swanson, G. A., Lodge, J. P., Jr., "Nitrite Interference in Spectrophotometric Determination of Atmospheric Sulfur Dioxide", *Anal. Chem.* 37, 943 (1965).
- (6) Zurlo, R., and Grifflin, A. M., "Measurement of the SO_2 Content of Air in the Presence of Oxides of Nitrogen and Hydrogen Sulfide", *Anal. Chem.* 35, 330 (1963).
- (7) Scarfingelli, P. F., Ziers, L., Norris, D., and Hochheiser, S., "Enhanced Sensitivity of Sulfur Dioxide in Solution", *Anal. Chem.* 42, 1818 (1970).
- (8) Lodge, J. P., Jr., Pata, J. E., Ammons, B. E., and Swanson, G. A., "Use of Hypodermic Needles as Critical Orifices in Air Sampling", *J. Air Poll. Cont. Assoc.* 16, 197 (1963).
- (9) O'Keefe, A. E., and Orman, O. C., "Primary Standards for Trace Gas Analysis", *Anal. Chem.* 38, 760 (1966).
- (10) Scarfingelli, P. F., Frey, S. A., and Saltzman, B. E., "Evaluation of Tedlar Permeation Tubes for Use with Sulfur Dioxide", *Amer. Ind. Hygiene Assoc. J.* 28, 260 (1967).
- (11) Scarfingelli, P. F., O'Keefe, A. E., Rosenber, E., and Bell, J. P., "Preparation and Use of Permeation Devices and Vapors with Permeation Devices Calibrated Gravimetrically", *Anal. Chem.* 42, 671 (1970).
- (12) Drone, P., Evans, J. E., and Noyes, C. M., "Tracer Techniques in Sulfur Dioxide Colorimetric and Conductometric Methods", *Anal. Chem.* 37, 1104 (1965).
- (13) Boström, C. E., "The Absorption of Sulfur Dioxide at Low Concentrations (p.p.m.) Studied by an Isotopic Tracer Method", *Intern. J. Air Water Poll.* 9, 83 (1968).

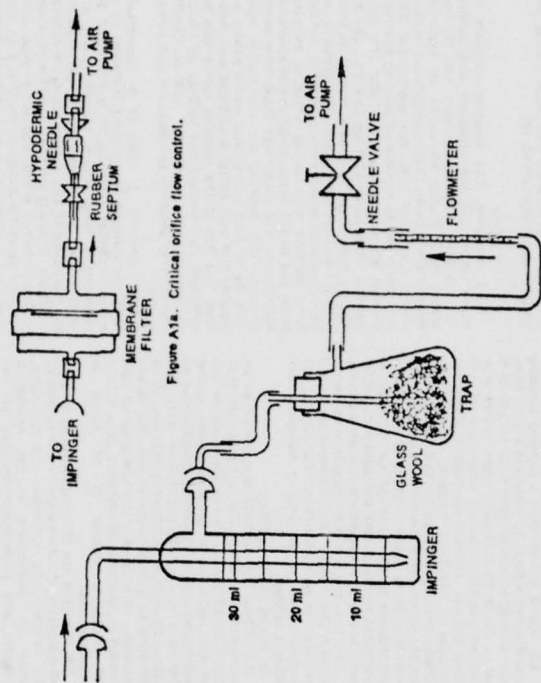


Figure A1a. Sampling train.

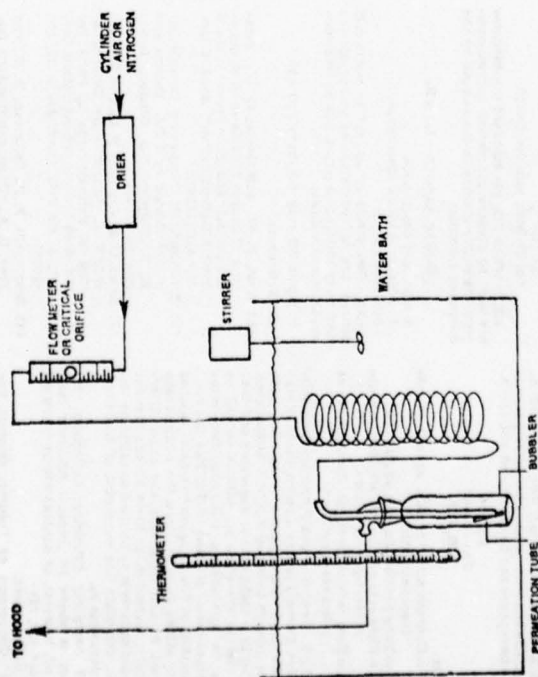


Figure A2. Apparatus for gravimetric calibration and field use.

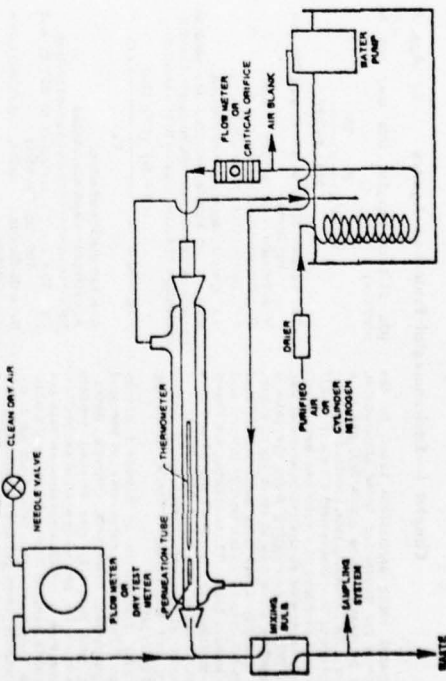


Figure A3. Preparation tube schematic for laboratory use.

APPENDIX B—REFERENCE METHOD FOR THE DETERMINATION OF SUSPENDED PARTICULATES IN THE ATMOSPHERE (HIGH VOLUME METHOD)

1. Principle and Applicability.

1.1 Air is drawn into a covered bounding and through a filter by means of a high-flow-rate blower at a flow rate (1.13 to 1.70 m³/min.; 40 to 60 ft.³/min.) that allows suspended particles having diameters of less than 100 μ m. (Stokes equivalent diameter) to pass to the filter surface. (1) Particles within the size range of 100 to 0.1 μ m. diameter are ordinarily collected on glass fiber filters. The mass concentration of suspended particulates in the ambient air (ag./m³) is computed by measuring the mass of collected particulates and the volume of air sampled. 1.2 This method is applicable to measurement of the mass concentration of suspended particulates in ambient air. The size of the sample collected is usually adequate for other analyses.

2. Range and Sensitivity.

2.1 When the sampler is operated at an average flow rate of 1.70 m³/min. (60 ft.³/min.) for 24 hours, an adequate sample will be obtained even in an atmosphere having concentrations of suspended particulates as low as 1 μ g./m³. If particulate levels are unusually high, a satisfactory sample may be obtained in 6 to 8 hours or less. For determination of average concentrations of suspended particulates in ambient air, a standard sampling period of 24 hours is recommended.

2.2 Weights are determined to the nearest milligram. Duplicate samples are determined to the nearest 0.01 m³ (0.35 ft.³). Times are determined to the nearest 2 minutes, and mass concentrations are reported to the nearest microgram per cubic meter.

3. Interferences.

3.1 Particulate matter that is oily, such as photochemical smog or wood smoke, may block the filter and cause a rapid drop in airflow at a nonuniform rate. Dense fog or high humidity can cause the filter to become too wet and severely reduce the airflow through the filter.

3.2 Glass-fiber filters are comparatively insensitive to changes in relative humidity, but collected particulates can be hygroscopic. (2)

4. Precision, Accuracy, and Stability.

4.1 Based upon collaborative testing, the relative standard deviation (coefficient of variation) for single analysis (variation of the method) is 10 percent. The relative standard deviation for laboratory variation (reproducibility of the method) is 2.7 percent. (3)

4.2 The accuracy with which the sampler measures the true average concentration depends upon the constancy of the airflow rate through the sampler. The airflow rate is affected by the concentration and the nature of the dust in the atmosphere. Under these

conditions the error in the measured average concentration may be in excess of ± 60 percent of the true average concentration, depending on the amount of reduction of airflow rate and on the variation of the mass concentration of dust with time during the 24-hour sampling period. (4)

5. Apparatus.

5.1.1 Sampler. The sampler consists of three units: (1) the faceplate and gasket, (2) the filter sampler assembly, and (3) the motor unit. Figure B1 shows an exploded view of these parts, their relationship to each other, and how they are assembled. The sampler must be capable of passing environmental air through a 406.5 cm.² (63 in.²) portion of a clean 20.3 by 25.4 cm. (8- by 10-in.) glass-fiber filter at a rate of at least 1.70 m³/min. (60 ft.³/min.). The motor must be capable of continuous operation for 24-hour periods with input voltages ranging from 110 to 120 volts, 50-60 cycles alternating current and must have third-wire safety ground. The housing for the motor unit may be of any convenient construction so long as the unit remains airtight and leak-free. The life of the sampler motor can be extended by lowering the voltage by about 10 percent with a small buck or boost transformer between the sampler and power outlet.

5.1.2 Sampler Shelter. It is important that the sampler be properly installed in a suitable shelter. The shelter is subjected to extremes of temperature, humidity, and all types of air pollution. For these reasons the materials of the shelter must be chosen carefully. Properly painted exterior plywood or heavy gauge aluminum serve well. The sampler must be mounted vertically in the shelter so that the glass-fiber filter is parallel with the ground. The shelter must be provided with a roof so that the filter is protected from precipitation and debris. The internal arrangement and configuration of the shelter must be such that a gale roof are shown in Figure B2. The clearances between the main housing and the roof at its closest point should be 580.5 \pm 103.5 cm.² (90 \pm 20 in.²). The main housing should be rectangular, with dimensions of about 24 by 83 cm. (11 $\frac{1}{2}$ by 14 in.).

5.1.3 Rotameter. Marked in arbitrary units, frequently 0 to 70, and capable of being calibrated. Other devices of at least comparable accuracy may be used.

5.1.4 Orifice Calibration Unit. Consisting of a metal tube 7.6 cm. (3 in.) ID and 18.3 cm. (6 $\frac{1}{2}$ in.) long with a static pressure tap 8.1 cm. (3 in.) from one end. See Figure B3. The tube end nearest the pressure tap is flanged to about 10.8 cm. (4 $\frac{1}{4}$ in.) OD with a standard 1.5 cm. (5/8 in.) diameter end of the high-volume sampler. The metal plate 9.2 cm. (3 $\frac{1}{2}$ in.) in diameter and 0.24 cm. (1 $\frac{1}{4}$ in.) thick with a central orifice 2.5 cm. (1 $\frac{1}{4}$ in.) in diameter is held in place at the air inlet end with a female threaded ring. The other end of the tube is flanged to

hold a loose female threaded coupling, which is placed on the back of the sampler, and read the rotameter ball with rotameter in a vertical position. Estimate to the nearest whole number. If the ball is fluctuating rapidly, stop the rotameter and slowly straighten it until the ball gives a constant reading. Disconnect the rotameter from the sampler; record the initial rotameter reading and the starting time and date on the filter folder. (The rotameter should never be connected to the sampler except when the flow is being measured.) Sample for 24 hours from the filter folder. Record the initial rotameter reading and the starting time and date on the filter folder.

Remove the facemask as described above and carefully remove the filter from the holder, leaving only the outer edge. Fold the filter lengthwise so that only surfaces with collected particulates are in contact, and place in a manila folder. Record on the folder the filter number, location, and any other factors, such as meteorological conditions or reading of nearby buildings, that might affect the results. If the sample is defective, void it at this time. In order to obtain a valid sample, the high-volume sampler must be operated with the same rotameter and filter tuning that was used during its calibration.

8.1.2 *Analysis.* Equivalents of suspended particulates for 24 hours of air conditioning are calculated from the filter conditioning factor, which is determined after they are analyzed. The filter may be saved for detailed chemical analysis.

8.1.3 *Rotameter.* Clean as required, using alcohol.

8.1.4 *Calibration.* Since only a small portion of the total air sampled passes through the rotameter during measurement, the rotameter must be calibrated against actual air flow with the orifice calibration unit. Before the orifice calibration unit can be used to calibrate the rotameter, the orifice calibration unit itself must be calibrated against the positive displacement primary standard.

8.1.5 *Orifice Calibration Unit.* Attach the orifice calibration unit to the intake end of the positive displacement primary standard and attach the high-volume sampler to the outlet. Connect one end of the primary standard to the orifice calibration unit and the other end to the atmosphere. Leave the high-volume motor blower unit so that a series of different, but constant, airflows (usually six) are obtained for definite time periods. Record the reading on the differential manometer at each airflow. The differential constant airflows are obtained by placing a

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series of loadplates, one at a time, between the calibration unit and the primary standard. Placing the pressure at the inlet reduces the pressure at the outlet of the primary standard below atmospheric; therefore, a correction must be made for the increase in volume caused by this decreased inlet pressure. Attach one end of a second differential manometer to an inlet pressure tap of the primary standard and leave the other open to the atmosphere. During each of the constant airflow measurements made above, measure the true inlet pressure of the primary standard with this second differential manometer. Measure atmospheric pressure and temperature. Correct the measured air volume to true air volume as directed in 9.1.1, then obtain true airflow rate, Q , as directed in 9.1.3.

8.1.2 *High-Volume Sampler.* Attach a high-volume sampler with a clean filter in place and run for at least 5 minutes. Attach ball reads 33, and seal the adjusting mechanism so that it cannot be changed easily. Shut off motor, remove the filter, and attach the orifice calibration unit in its place. Operate the high-volume sampler at a series of different, but constant, airflows (usually six). Record the reading of the differential manometer on the orifice calibration unit, and record the readings of the rotameter at each flow. Measure atmospheric pressure and temperature. Convert the differential manometer reading to m^3/min , Q , then plot rotameter reading versus Q .

8.1.3 *Correction for Differences in Pressure or Temperature.* See Addendum B.

9.1.1 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.2 *Calibration.* See Addendum B.

9.1.3 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.4 *Calibration.* See Addendum B.

9.1.5 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.6 *Calibration.* See Addendum B.

9.1.7 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.8 *Calibration.* See Addendum B.

9.1.9 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.10 *Calibration.* See Addendum B.

9.1.11 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.12 *Calibration.* See Addendum B.

9.1.13 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.14 *Calibration.* See Addendum B.

9.1.15 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.16 *Calibration.* See Addendum B.

9.1.17 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.18 *Calibration.* See Addendum B.

9.1.19 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.20 *Calibration.* See Addendum B.

9.1.21 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.22 *Calibration.* See Addendum B.

9.1.23 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.24 *Calibration.* See Addendum B.

9.1.25 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

9.1.26 *Calibration.* See Addendum B.

9.1.27 *True Air Volume.* Calculate the air volume measured by the positive displacement primary standard.

Q = Flow rate, m^3/min .

T = Time of flow, min.

9.2 *Sample Volume.*

9.2.1 *Volume Conversion.* Convert the initial and final rotameter readings to true airflow rate, Q , using calibration curve of 9.1.1.

9.2.2 *Calculate volume of air sampled*

$V = \frac{Q \cdot T}{2}$

V = Air volume sampled, m^3 .

Q = Initial airflow rate, m^3/min .

T = Sampling time, min.

9.3 *Calculate mass concentration of suspended particulates*

$S.P. = \frac{(W_1 - W_2) \times 10^6}{V}$

$S.P.$ = Mass concentration of suspended particulates, mg/m^3 .

W_1 = Initial weight of filter, g.

W_2 = Final weight of filter, g.

V = Air volume sampled, m^3 .

10^6 = Conversion of g to mg .

10. *References.*

(1) Robson, G. D., and Foster, K. Z., "Evaluation of Air Particulate Sampling Equipment", *Am. Ind. Hyg. Assoc. J.* 24, 404 (1962).

(2) Tormay, G. P., and Conner, W. D., "Hygroscopic Effects on Weight Determinations of Particulates Collected on Glass-Fiber Filters", *Am. Ind. Hyg. Assoc. J.* 23, 863 (1962).

(3) Unpublished data based on a collaborative test involving 12 participants, conducted under the direction of the Methods Subcommittee, American Society of Mechanical Engineers, Air Pollution Control Administration, October, 1970.

(4) Harrison, W. K., Nader, J. S., and Ferguson, P. B., "Comparison of Rotameters for High-Volume Air Sampling", *Am. Ind. Hyg. Assoc. J.* 21, 114-120 (1960).

(5) Fack, J. B., and Tabor, K. O., "Analytical Aspects of the Use of Glass-Fiber Filters for the Collection and Analysis of Atmospheric Particulate Matter", *Am. Ind. Hyg. Assoc. J.* 22, 144-150 (1961).

Appendix

A. *Alternative Equipment.*

A modification of the high-volume sampler incorporating a method for recording the actual airflow over the entire sampling period has been described, and is acceptable for measuring the concentration of suspended particulates (Henderson, J. S., *High-Volume Sampling Methods in Air Pollution and Industrial Hygiene Studies*, 1967, Oakland,

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Calif.). This modification consists of an exhaust orifice meter assembly connected through a transducer to a system for continuously recording airflow on a circular chart. The volume of air sampled is calculated by the following equation:

$$V = Q \times T$$

Q = Average sampling rate, m./min.

T = Sampling time, minutes.

The average sampling rate, Q, is determined from the recorder chart by estimation if the flow rate does not vary more than 0.1 m./min. (1 ft./min.) during the sampling period. If the flow rate does vary more than 0.1 m./min. (1 ft./min.) during the sampling period, read the flow rate from the chart at 2-hour intervals and take the average.

B. Pressure and Temperature Corrections. If the pressure or temperature during high-volume sampler calibration is substantially different from the pressure or temperature during orifice calibration, a correction of the flow rate, Q, may be required. If the pressures differ by no more than 15 percent and the temperatures differ by no more than 100 percent (°C), the error in the un-

corrected flow rate will be no more than 15 percent. If necessary, obtain the corrected flow rate as directed below. This correction applies only to orifice meters having a constant orifice coefficient. The coefficient for the calibrating orifice described in 8.1.4 has been shown experimentally to be constant over the normal operating range of the high-volume sampler (0.6 to 2.2 m./min.; 20 to 76 ft./min.). Calculate corrected flow rate:

$$Q_c = Q \left[\frac{T_c P_c}{T P} \right]^{1/4}$$

Q_c = Corrected flow rate, m./min.

Q = Flow rate during high-volume sampler calibration (Section 8.1.2), m./min.

T_c = Absolute temperature during orifice unit calibration (Section 8.1.1), °K or °R.

P_c = Barometric pressure during orifice unit calibration (Section 8.1.1), mm. Hg.

T = Absolute temperature during high-volume sampler calibration (Section 8.1.2), °K or °R.

P = Barometric pressure during high-volume sampler calibration (Section 8.1.2), mm. Hg.

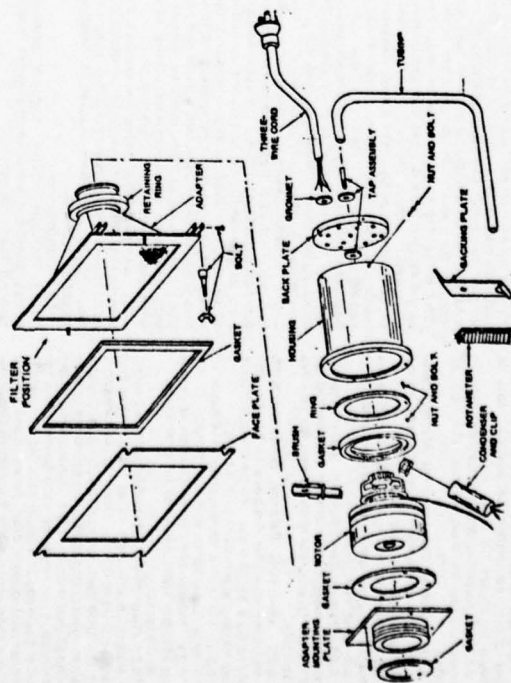


Figure B1. Exploded view of typical high-volume air sampler parts.

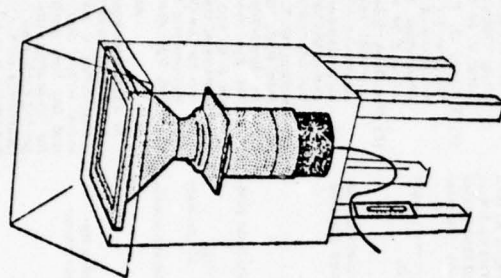


Figure B2. Assembled sampler and shelter.

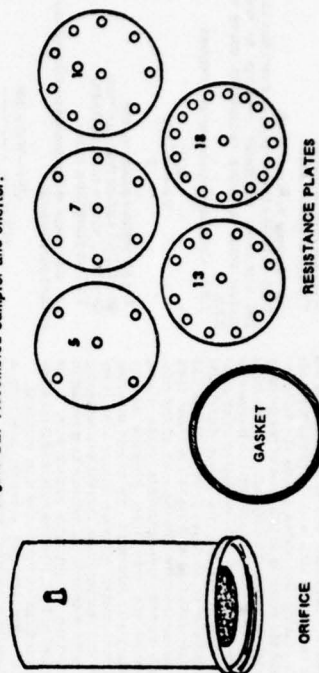


Figure B3. Orifice calibration unit.

APPENDIX C—MEASUREMENT PRINCIPLES AND CALIBRATION PROCEDURES FOR THE COMBUSTION MEASUREMENT OF CARBON MONOXIDE IN THE ATMOSPHERE (NON-DESTRUCTIVE INFRARED SPECTROMETRY)

1. Principle. This principle is based on the absorption of infrared radiation by carbon monoxide in a non-dispersive photometer. Both beams pass into matched cells, each containing a selective detector and CO. The CO in the cells absorb infrared radiation only at its characteristic frequencies and the detector is sensitive to those frequencies. With a non-absorbing gas in the reference cell, and with no CO in the sample cell, the signals from both detectors are balanced electronically. Any CO introduced into the sample cell will absorb radiation, which reduces the temperature and produces a signal. This displacement is detected electronically and amplified to provide an output signal.

1.1 This principle is based on this principle will be considered a reference method only if it has been designated as a reference method in accordance with Part 53 of this chapter.

2.—6. [Reserved]

7. Procedure.

7.1 Calibrate the instrument as described in 8.1. All gases (sample, zero, calibration, and span) must be introduced into the entire analyzer system. Figure C1 shows a typical flow diagram. For specific operating instructions, refer to the manufacturer's manual.

8. Calibration.

8.1 Calibration Curve. Determine the linearity of the detector response at the operating flow rate and temperature. Prepare a calibration curve and check the curve furnished with the instrument. Introduce zero gas and set the zero control to indicate a recorder reading of zero. Introduce span gas and adjust the span control to indicate the proper value on the recorder scale (e.g., on 0-50 mg./m.³ scale, set the 45 mg./m.³ standard at 90 percent of the recorder range). Recheck zero and span until adjustments are no longer necessary. Introduce intermediate calibration gases and plot the obtained. If enough points are not obtained, calibration gases may need replacement.

9. Calculations.

9.1 Determine the concentrations directly from the calibration curve. No calculations are necessary.

9.2 Carbon monoxide concentrations in mg./m.³ are converted to p.p.m. as follows:

$$\text{p.p.m. CO} = \text{mg. CO/m}^3 \times 0.877$$

10. Bibliography.

The Intech NDIR-CO Analyzer by Frank McElroy. Presented at the 11th Methods Conference in Air Pollution, University of California, Berkeley, Calif., April 1, 1970. Jacobs, M. and M. J.A.P.O.A. P. No. 2, 110-114, August 1969.

MSA LIRA Infrared Gas and Liquid Analyzer Instruction Book, Mine Safety Appliances Co., Pittsburgh, Pa.

Beckman Instruction 10339, Models 315A, 315A and 415A Infrared Analyzers, Beckman Instrument Company, Fullerton, Calif.

Continuous CO Monitoring System, Model A 5811, Intertech Corp., Princeton, N.J.

Bendix-UNOR Infrared Gas Analyzer, Bendix-Wallace, W. Va.

[35 FR 22394, Nov. 25, 1971, as amended at 40 FR 7043, Feb. 18, 1975]

APPENDIX D—MEASUREMENT PRINCIPLE AND CALIBRATION PROCEDURE FOR THE MEASUREMENT OF PHOTOCHEMICAL OXIDANTS CORRELATED FOR INTERFERENCES DUE TO NITROGEN OXIDES AND SULFUR DIOXIDES

1.1 Ambient air and ethylene are delivered simultaneously to a mixing zone where the ozone in the air reacts with the ethylene to emit light which is detected by a photomultiplier tube. The resulting photocurrent is amplified and is either read directly or displayed on a recorder.

1.2 An analyzer based on this principle will be considered a reference method only if it has been designated as a reference method in accordance with Part 53 of this chapter.

2.—4. [Reserved]

5. Apparatus.

5.1—5.9 [Reserved]

6.10 Apparatus for Calibration.

6.10.1 Absorber. All-glass impingers as shown in Figure D4 are recommended. The impingers may be purchased from most major glassware suppliers. Two absolute collations are needed to insure complete collection of the sample.

6.10.2 Air Pump. Capable of drawing 1 liter/minute through the absorber. The pump should be equipped with a needle valve on the inlet side to regulate flow.

6.10.3 Thermometer. With an accuracy of $\pm 0.3^\circ \text{C}$.

6.10.4 Barometer. Accurate to the nearest mm. Hg.

6.10.5 Flowmeter. Calibrated metering device for measuring flow up to 1 liter/minute within ± 2 percent. (For measuring flow through impingers.)

6.10.6 Flowmeter. For measuring airflow from the impinger, must be capable of measuring flow from 2 to 10 liter/minute within ± 3 percent.

6.10.7 Trap. Containing glass wool to protect needle valve.

6.10.8 Volumetric Flask. 25, 100, 500, 1,000 ml.

6.10.9 Buret. 50 ml.

6.10.10 Pipette. 0.1, 1, 2, 5, 10, 25, and 50 ml. volumetric.

6.10.11 Erlenmeyer Flask. 300 ml.

6.10.12 Spectrophotometer. Capable of measuring absorbance at 352 nm. Matched 1-cm. cells should be used.

6. Reagents.

6.1 Ethylene. C. P. grade (minimum).

6.3 Cylinder Air. Dry grade.
6.5 Activated Charcoal. Prep. For Allowing cylinder air.
Normality $\text{As}_2\text{O}_3 \times \text{Normality As}_2\text{O}_3$
ml. L

6.9 Diluted Standard Iodine. Immediately before use, pipet 1 ml. standard iodine solution into a 100-ml. volumetric flask and dilute to volume with absorbing reagent.

7. Procedure.

7.1 Instruments can be constructed from the components given here or may be purchased. If commercial instruments are used, follow the specific instructions given in the manufacturer's manual. Calibrate the instrument as directed in section 8. Introduce samples into the system under the same conditions of pressure and flow rate as are used in calibration. By proper adjustments of zero and span controls, direct readings of ozone concentration is possible.

8. Calibration.

8.1 KI Calibration Curve. Prepare a curve of absorbance of various iodine solutions against calculated ozone equivalents as follows:

8.1.1 Into a series of 25 ml. volumetric flasks, pipet 0.5, 1, 2, 3, and 4 ml. of diluted standard iodine solution (6.9). Dilute each to the mark with absorbing reagent. Mix thoroughly, and immediately read the absorbance of each at 352 nm. against unabsorbed absorbing reagent as the reference.

8.1.2 Calculate the concentration of the solutions as total As_2O_3 as follows:

$$\text{Total } \text{As}_2\text{O}_3 = (N) (V_1) / V_2$$

N = Normality I_2 (see 6.9.3), meq./ml.
 V_1 = Volume of diluted standard I_2 added, ml. (0.5, 1, 2, 3, 4).

Plot absorbance versus total As_2O_3 .

8.2 Instrument Calibration.

8.2.1 Generation of Test Atmospheres. Assemble the apparatus as shown in Figure D8. The ozone concentration produced by the generator can be varied by changing the position of the adjustable screw. For accurate results, the generator should be capable of producing ozone concentrations in the range 100 to 1,000 $\mu\text{g./m}^3$ (0.03 to 0.5 p.p.m.) at a flow rate of at least 5 liters per minute. At all times the airflow through the generator must be greater than the total flow required by the sampling system.

8.2.2 Sampling and Analysis of Test Atmospheres. Assemble the KI sampling train as shown in Figure D4. Use ground-glass connections upstream from the impinger. But-to-but connections with Tygon tubing may be used. The manifold distributing the test atmosphere must be sampled simultaneously by the KI sampling train and the instrument to be calibrated. Check assembly for leaks. Record the absorbance readings in the instrument.

8.2.3 Establish three concentrations by analysis, using the new-

trial buffered potassium iodide method as follows:

8.2.2.1 Blank. With ozone lamp off, flush the system for several minutes to remove residual ozone. Pipet 10 ml. absorbing reagent into each absorber. Draw air from the ozone-generating system through the sampling train at 2 to 4 liters per minute for 10 minutes. Transfer the exposed solution to a clean 1-cm. cell. Determine the absorbance at 353 nm. against unexposed absorbing reagent as the reference. If the system blank gives an absorbance, continue flushing the ozone generation system until no absorbance is obtained.

8.2.2.2 Test Atmosphere. With the ozone lamp operating, equilibrate the system for about 10 minutes. Pipet 10 ml. of absorbing reagent into each absorber and collect samples for 10 minutes in the concentration range desired for calibration. Immediately transfer the solutions from the two absorbers to clean 1-cm. cells. Determine the absorbance of each at 353 nm. against unexposed absorbing reagent as the reference. Add the absorbances of the two solutions to obtain total absorbance. Read total $\mu\text{g O}_3$ from the calibration curve (see 8.1). Calculate total volume of air sampled corrected to reference conditions of 26° C. and 760 mm. Hg. as follows:

$$V_a = V \times \frac{P}{760} \times \frac{298}{t + 273} \times 10^{-4}$$

V_a = Volume of air at reference conditions, m^3
 V = Volume of air at sampling conditions, liters
 P = Barometric pressure at sampling conditions, mm. Hg.
 t = Temperature at sampling conditions, °C.
 10^{-4} = Conversion of liters to m^3 .

Calculate ozone concentration in p.p.m. as follows:

$$\text{p.p.m. O}_3 = \frac{\mu\text{g O}_3}{V_a} \times 8.10 \times 10^{-4}$$

8.2.3 Instrument Calibration Curve. Instrument response from the photomultiplier tube is ordinarily in current or voltage. Plot the current, or voltage if appropriate, (y-axis) for the test atmosphere against ozone concentration as determined by the neutral buffered potassium iodide method, in p.p.m. (x-axis).

9. Calculations.
 9.1 If a recorder is used which has been properly zeroed and spanned, ozone concentrations can be read directly.

9.2 If this DC amplifier is read directly, the reading must be converted to ozone concentrations using the instrument calibration curve (8.2.3), between p.p.m. and $\mu\text{g}/\text{m}^3$ values for ozone can be made as follows:

$$\text{p.p.m. O}_3 = \frac{\mu\text{g O}_3}{\text{m}^3} \times 8.19 \times 10^{-4}$$

10. Bibliography.

- Hodgeson, J. A., Martin, B. E., and Baumgardner, R. E., "Comparison of Chemiluminescent Methods for Measurements of Atmospheric Ozone", Preprint, Eastern Analytical Symposium, New York, N.Y., October, 1970.
 Hodgeson, J. A., Stevens, B. E., and Martin, B. E., "A Stable Ozone Source Applicable as a Secondary Standard for Calibration of Atmospheric Monitors", Preprint No. 71-800, Instrument Society of America, International Conference and Exhibit, Chicago, Ill., October, 1971.
 Niederbragt, G. W., Van der Horst, A., and Van Duyn, J., *Nature* 205, 87 (1965).
 Warren, O. J., and Babcock, G., *Rev. Sci. Instr.* 41, 280 (1970).

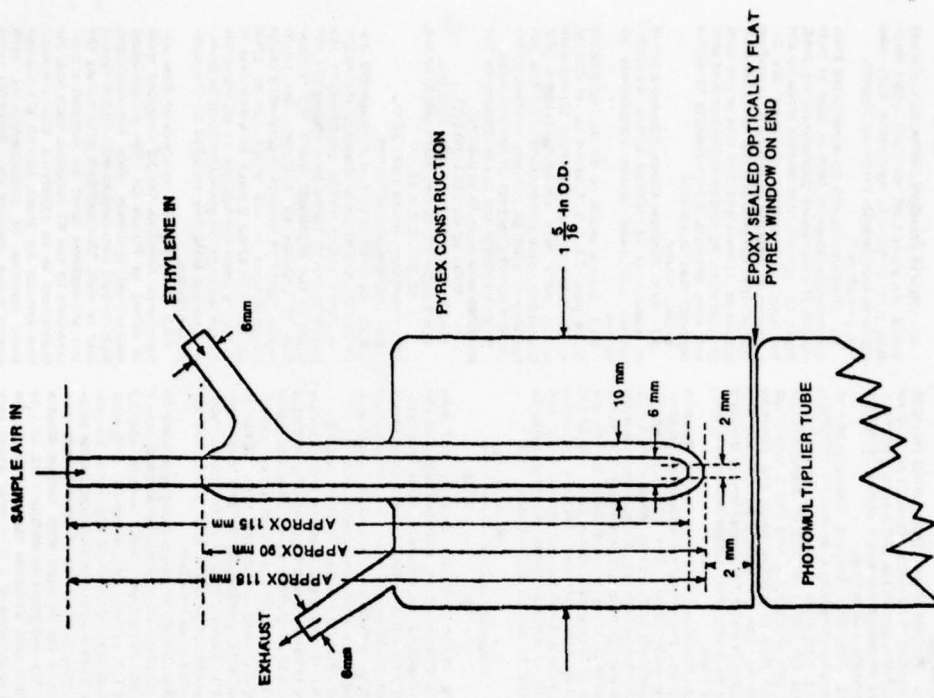


Figure D1. Detector cell.
 [56 FR 22384, Nov. 25, 1971, as amended at 40 FR 7043, Feb. 18, 1975]

APPENDIX E—REFERENCE METHODS FOR DETERMINATION OF HYDROCARBONS COLLECTED FOR METHANE

1. Principle and Applicability

1.1 Measured volumes of air are delivered semicontinuously (4 to 12 times per hour) to a hydrogen flame ionization detector to measure its total hydrocarbon (THC) content. An aliquot of the same air sample is introduced into a stripper column which removes water, carbon dioxide, and hydrocarbons other than methane. Methane and carbon monoxide are passed quantitatively to a gas chromatographic column where they are separated. The methane is eluted first, and is passed unchanged through a catalytic detector. The carbon monoxide is eluted into the catalytic reduction tube where it is reduced to methane before passing through the flame ionization detector. Between analyses the stripper column is backflushed to prepare it for subsequent analysis. Hydrocarbon concentrations corrected for methane are determined by subtracting the methane value from the total hydrocarbon value. Two modes of operation are possible: (1) A complete chromatographic analysis showing the continuous output from the detector for each sample injection; (2) The system is programmed for automatic zero and span to display selected band widths of the chromatogram. The latter mode is used as the former operation is referred to as the chromatographic or "normal" mode depending on the make of analyzer.

1.2 The method is applicable to the semicontinuous measurement of hydrocarbons corrected for methane in ambient air. The carbon monoxide measurement, which is simultaneously obtained in this method, is not required in making measurements of hydrocarbons corrected for methane and will not be dealt with here.

2. Range and Sensitivity

2.1 Instruments are available with various range combinations. For atmospheric analysis the THC range is 0-131 mg/m³ (0-20 p.p.m.) carbon (as CH₄) and the methane range is 0-0.05 mg/m³ (0-10 p.p.m.). For special applications, lower ranges are available and in these applications the range for THC is 0-131 mg/m³ (0-20 p.p.m.) carbon (as CH₄) and for methane the range is 0-131 mg/m³ (0-20 p.p.m.).

2.2 For the higher, atmospheric analysis ranges the sensitivity for THC is 0.005 mg/m³ (0.1 p.p.m.) carbon (as CH₄) and for methane the sensitivity is 0.003 mg/m³ (0.05 p.p.m.). For the lower, special analysis ranges the sensitivity is 0.016 mg/m³ (0.025 p.p.m.) for each gas.

3. Interferences

3.1 No interference in the methane measurement has been observed. The THC measurement typically includes all or a portion of what is generally classified as the air peak interference. This effect is minimized by proper plumbing arrangements or is negated electronically. Accuracy and Stability

4.1 Precision determined with calibration gases is ±0.6 percent of full scale in the higher, atmospheric analysis ranges. 4.2 Accuracy is dependent on instrument linearity and absolute concentration of the calibration gases. An accuracy of 1 percent of full scale in the higher, atmospheric analysis ranges and 2 percent of full scale in the lower, special analysis ranges can be obtained.

4.3 Variations in ambient room temperature can cause changes in performance characteristics. This is due to shifts in oven temperature, flow rates, and pressure with ambient temperature change. The instrument should meet performance specifications with room temperature changes of ±3° C. Baseline drift is automatically corrected in the chromatographic mode.

5.1 Commercially Available THC, CH₄, and CO Analyzers Instruments should be sealed on location and demonstrated, preferably by the manufacturer, or his representative, to meet or exceed manufacturer's specifications and those described in this method.

5.2 Sample Introduction System. Pump, flow control valves, automatic switching valves, and flowmeter.

5.3 Filter (in-line). A binder-free, glass-fiber filter with a porosity of 3 to 5 microns should be immediately downstream from the sample pump.

5.4 Stripper or Precolumn. Located outside of the oven at ambient temperature. The column should be replaced or replaced after the equivalent of 2 months of continuous operation.

5.5 Oven. For containing the analytical column and catalytic converter. The oven should be capable of maintaining a constant temperature constant within ±0.2° C. The specific temperature varies with instrument manufacturer.

6. Reagents

6.1 Combustion Gas. Air containing less than 1.5 mg/m³ (2 p.p.m.) hydrocarbon as methane.

6.2 Fuel. Hydrogen or a mixture of hydrogen and inert gas containing less than 0.005 mg/m³ (0.1 p.p.m.) hydrocarbons as methane.

6.3 Carrier Gas. Helium, nitrogen, air or hydrogen containing less than 0.005 mg/m³ (0.1 p.p.m.) hydrocarbons as methane.

6.4 Zero Gas. Air containing less than 0.005 mg/m³ (0.1 p.p.m.) total hydrocarbons as methane.

6.5 Calibration Gases. Gases needed for linearity checks (peak heights) are determined by the ranges used. Calibration gases corresponding to 10, 20, 40, and 80 percent of full scale are used. Calibration gases should include a mixture of methane and hydrocarbon. Methane is used for both the total hydrocarbon measurement and methane measurement.

6.6 Span Gas. The calibration gas corresponding to 80 percent of full scale is used to span the instrument.

7. Procedure

7.1 Calibrate the instrument as described in 8.1. Introduce sample into the system under the same conditions of pressure and flow rates as are used in calibration. (The pump is bypassed only when pressurized cylinders gases are used.) Figure E1 shows a typical flow diagram; for specific operating instructions refer to manufacturer's manual.

8. Calibration

8.1 Calibration Curve. Determine the linearity of the system for THC and methane in the chromatographic mode by introducing zero gas and adjusting the respective zeroing controls to indicate a recorded reading of zero. Control the flow rate by adjusting the flow control to indicate the proper value on the recorder scale. Record zero and span until adjustments are no longer necessary. Introduce intermediate calibration gases and plot the values obtained. If a smooth curve is not obtained, calibration gases may need replacement.

9. Calculation

9.1 Determine concentrations of total hydrocarbons (as CH₄) and CH₄ directly from the calibration curve. No calculations are necessary.

9.2 Determine concentration of hydrocarbons corrected for methane by subtracting the methane concentration from the total hydrocarbon concentration.

9.3 Conversion between p.p.m. and mg/m³ values for total hydrocarbons (as CH₄) and methane are made as follows:

p.p.m. carbon (as CH₄) = [mg. carbon (as CH₄)/m³] × 1.25

10. Bibliography

Few, O., "Multi-Parameter Air Quality Analyzer", ISA Proceedings AID/CHEMPID Symposium, Houston, Texas, April 19-21, 1971.

Villalobos, R. and Chapman, R. L., "A Gas Chromatographic Method for Automatic

Monitoring of Pollutants in Ambient Air", *ibid.*

Stevens, R. K., "The Automated Gas Chromatograph as an Air Pollutant Monitor", 1970 Conference on Environmental Toxicology, 1970, Air Force, Wright-Patterson Air Force Base, Dayton, Ohio.

Sizemore, R. K., O'Keefe, A. E., *Anal. Chem.* 42, 133A (1970).

Schnick, E. A., Altmiller, A. P., Barth, D. S., and Morgan, G. B., "Seasonal Study of Hydrocarbons to Oxidants in Ambient Atmospheres", *J. Air Poll. Cont. Assoc.* 20, 297-302 (1970).

O. C., "A Gas Chromatographic Approach to the Semi-Continuous Monitoring of Atmospheric Carbon Monoxide and Methane", Proceedings of 11th Conference on Methods in Air Pollution on Industrial Hygiene Studies, Berkeley, Calif., March 30-April 1, 1970.

Swierczek, J. W., Linnebach, V. J., and Glick, C. H., *Environ. Sci. Technol.* 3, 836 (1969).

Williams, I. O., Adams, J. N., Chromatography, Giddings, J. C., and Keller, R. A., editors, Marcel Dekker, N.Y. (1968), pp. 178-182.

Altmiller, A. P., Kopczak, S. L., Lonnebach, W. A., Becker, T. L., and Slater, R., *Environ. Sci. Technol.* 1, 899 (1967).

Altmiller, A. P., Cohen, I. R., and Purcell, T. C., *Can. J. Chem.* 44, 2773 (1966).

Drabos, L., Zdrojewski, A., and Monkmann, J. L., *J. Air Poll. Cont. Assoc.* 16, 135 (1966).

Ottman, G. C., *Anal. Chem.* 38, 644-646 (1966).

M. J. K. and Volman, D. H., *Anal. Chem.* 38, 1449 (1966).

Crump, W. M., Proceedings, National Analytical Instrumentation Symposium, ISA, 1962.

Schwink, A., Hochberg, H., and Forderer, M., *Environ.-Chimie* 71, No. 9, 295 (1961).

Instruction Manual for Air Quality Chromatograph Model 6800, Beckman Instrument Co., Fullerton, Calif.

Instruction Manual, Bendix Corp., Riverside, W. Va.

Instruction Manual, Byron Instrument Co., Raleigh, N.C.

ISA Instruction Manual for GC Process Analyzer for Total Hydrocarbon, Methane and Carbon Monoxide, Pittsburgh, Pa.

Monsanto Environ-Chem System for Total Hydrocarbons, Methane and Carbon Monoxide Instruction Manual, Dayton, Ohio.

Union Carbide Chromatograph Instruction Manual for Model 6800, Chromatograph for CO-CH₄-7/1 White Plains, N.Y.

Instruction Manual for 560 F Analyzer, Trace Inc., Austin, Tex.

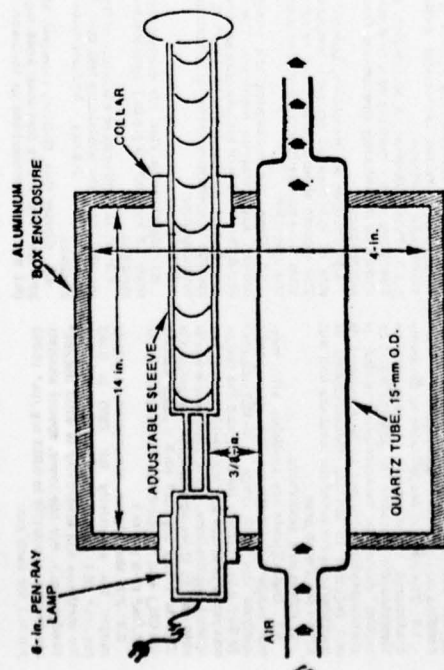


Figure D2. Ozone source.

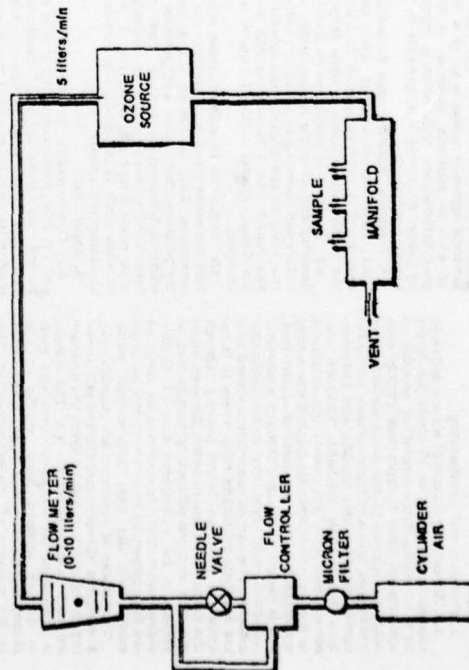


Figure D3. Ozone calibration air supply, source, and manifold system.

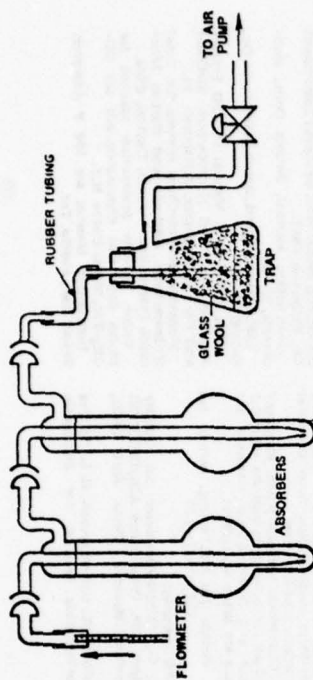


Figure D4. KI sampling train.

A. Suggested Performance Specifications for Atmospheric Analyzers for Hydrocarbons Corrected for Methane:

Range (minimum)-----	0.3 mg/m ³ (0-5 p.p.m.) THC
Output (minimum)-----	0-3 mg/m ³ (0-5 p.p.m.) CH ₄
Minimum detectable sensitivity.	0.1 p.p.m. THC.
Zero drift (maximum) --	Not to exceed 1 percent/24 hours.
Span drift (maximum) --	Not to exceed 1 percent/24 hours.
Precision (minimum) --	±0.5 percent.
Operational period (minimum).	3 days.
Operating temperature range (minimum).	5-40° C.
Operating humidity range (minimum).	10-100 percent.
Linearity (maximum) --	1 percent of full scale.

B. Suggested Definitions of Performance Specifications:

Range—The minimum and maximum measurement limits.

Output—Electrical signal which is proportional to the measurement; intended for connection to readout or data processing devices. Usually expressed as millivolts or milliwatts full scale at a given impedance.

Full Scale—The maximum measuring limit for a given range.

Minimum Detectable Sensitivity—The smallest amount of input concentration that can be detected as the concentration approaches zero.

Accuracy—The degree of agreement between a measured value and the true value; usually expressed as ± percent of full scale.

Lag Time—The time interval from a step change in input concentration at the instrument inlet to the first corresponding change in the instrument output.

Time to 90 Percent Response—The time interval from a step change in the input concentration at the instrument inlet to a reading of 90 percent of the ultimate recorded concentration.

Rise Time (90 percent)—The interval between initial response time and time to 90 percent response after a step decrease in the inlet concentration.

Zero Drift—The change in instrument output over a stated time period, usually 24 hours, of unadjusted continuous operation, when the input concentration is a stated full scale value; usually expressed as percent full scale.

Precision—The degree of agreement between repeated measurements of the same concentration. It is expressed as the standard deviation of the single results from the mean.

Operational Period—The period of time over which the instrument can be expected to operate unattended within specifications.

Noise—Spontaneous deviations from a mean output not caused by input concentration changes.

Interference—An undesired positive or negative output caused by a substance other than the one being measured.

Interference Equivalent—The portion of indicated input concentration due to the presence of an interferent.

Operating Temperature Range—The range of ambient temperatures over which the instrument will meet all performance specifications.

Operating Humidity Range—The range of ambient relative humidity over which the instrument will meet all performance specifications.

Linearity—The maximum deviation between an actual instrument reading and the reading predicted by a straight line drawn between upper and lower calibration points.

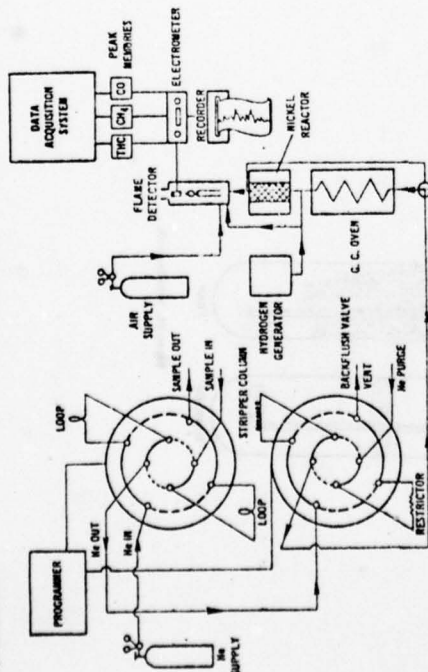


Figure E1. Typical Flow Diagram.

APPENDIX F—REFERENCE METHOD FOR THE DETERMINATION OF NITROGEN DIOXIDE IN THE ATMOSPHERE (24-HOUR SAMPLING METHOD)

1. **Principle and Applicability.**
 - 1.1 Nitrogen dioxide is collected by bubbling air through a sodium hydroxide solution to form a sodium nitrite solution. The nitrite is then produced during sampling by the action of a reagent with the exposed absorbing reagent with phosphoric acid, sulfanilamide, and N-1-naphthylethylenediamine dihydrochloride.
 - 1.2 The method is applicable to collection of 24-hour samples in the field and subsequent analysis in the laboratory.
2. **Range and Sensitivity.**
 - 2.1 The range of the analysis is 0.04 to 1.5 μg NO_2/m^3 . With 50 ml. absorbing reagent and a sampling rate of 200 ml./min. for 24 hours, the range of the method is 20–140 $\mu\text{g}/\text{m}^3$ (0.01–0.4 ppm.) nitrogen dioxide.
 - 2.2 A concentration of 0.04 μg NO_2/m^3 will produce an absorbance of 0.02 using 1-cm. cells.
3. **Interferences.**
 - 3.1 The interference of sulfur dioxide is eliminated by converting it to sulfuric acid with hydrogen peroxide before analysis.
4. **Precision, Accuracy, and Stability.**
 - 4.1 The relative standard deviations are 14.4 percent and 21.5 percent at nitrogen dioxide concentrations of 140 $\mu\text{g}/\text{m}^3$ (0.073

*Available from Bel-Art Products, Pequannock, N.J.

maximum pore diameter, $\mu\text{m} = \frac{308}{P}$

P—Surface tension of water in dynes/cm. at the test temperature (73 at 18° C., 72 at 20° C., and 71 at 31° C.).

P—Measured vacuum, mm. Hg.

8.1.3 Probe. Teflon, polypropylene, or glass tube with a polypropylene or glass funnel at the end and a membrane filter to protect the frit. Replace filter after collecting five samples, or more often as indicated by visual observation of the loading.

8.1.5 Flow Control Device. Calibrated 27-gauge hypodermic needle, three-eighths of an inch long to maintain a flow of approximately 0.2 liter/minute. Needle should be protected by a cap. Change filter after collecting 10 samples.

8.1.4 Air Pump. Capable of maintaining a flow of 0.2 liter/minute through the absorber, and a vacuum of 0.7 atmosphere.

8.1.6 Calibration Equipment. Glass flowmeter for measuring airflow up to approximately 275 ml./min. within ± 2 percent, stopwatch, and precision wet test meter (1 liter/revolution).

8.2 Analysis.

8.2.1 Volumetric Flasks. 50, 100, 200, 250, 500, 1,000 ml.

8.2.2 Graduated Cylinder. 1,000 ml.

8.2.3 Pipets. 1, 2, 5, 10, 15 ml. volumetric; 3 ml. graduated in 1/10 ml. intervals.

8.2.4 Test Tube.

8.2.5 Spectrophotometer or Colorimeter. Capable of measuring absorbance at 640 nm. Bandwidth is not critical.

8. Reagents.

8.1.1 Absorbing Reagent. Dissolve 4.0 g. sodium hydroxide in distilled water and dilute to 1,000 ml.

8.2 Analysis.

8.2.1 Sulfanilamide. Dissolve 20 g. sulfanilamide in 700 ml. distilled water. Add with mixing, 50 ml. concentrated phosphoric acid (85 percent) and dilute to 1,000 ml. This solution is stable for a month if refrigerated.

8.2.2 NEDA Solution. Dissolve 0.5 g. N-1-naphthylethylenediamine dihydrochloride in 800 ml. of distilled water. This solution is stable for a month if refrigerated and protected from light.

8.2.3 Hydrogen Peroxide. Dilute 0.2 ml. 30 percent hydrogen peroxide to 250 ml. with distilled water. This solution may be used for a month if protected from light.

8.2.4 Standard Nitrite Solution. Dissolve 0.14 g. standardized sodium nitrite (NaNO_2 , standard 99 percent or greater) and dilute with distilled water to 100 ml. This solution containing 1,000 μg NO_2/m^3 is obtained. The amount of NaNO_2 to use is calculated as follows:

$$G = \frac{1,500 \times 100}{A}$$

G—Amount of NaNO_2 , g.

1,500—Gravimetric factor in converting

NO_2 into NaNO_2 ,
A=Assay, percent.

7. Procedure.

7.1 Sampling. Assemble the sampling train as shown in Figure F1. Add 50 ml. absorbing reagent to the absorber. Disconnect funnel, insert calibrated flowmeter, and measure flow before sampling. If flow rate before sampling is less than 80 percent of needed calibration, check for leak or change needed calibration. Replace flowmeter and replace funnel. Sample for 24 hours from midnight to midnight and measure flow at end of sampling period.

7.2 Analysis. Replace any water lost by evaporation during sampling. Pipet 10 ml. of the collected sample into a test tube. Add 1.0 ml. hydrogen peroxide solution, 10.0 ml. sulfanilamide solution, and 1.4 ml. NEDA solution with thorough mixing after the addition of each reagent. Prepare a blank in the same manner using 10 ml. absorbing reagent. After a 10-minute color-development interval, measure the absorbance at 640 nm. against the blank. Read μg NO_2/m^3 from standard curve (Section 8.2).

8. Calibration and Epitomes.

8.1 Sampling.

8.1.1 Calibration of Flowmeter. Using a wet test meter and a stopwatch, determine the rate of air flow (ml./min.) through the flowmeter at several ball positions. Plot ball positions versus flow rate.

8.1.2 Calibration of Hypodermic Needle. Connect the calibrated flowmeter, the needle to be calibrated, and the section of vacuum tubing in such a way that the direction of air flow through the needle is the same as in the sampling train. Read the position of the ball and determine flow rate in ml./min. from the calibration chart prepared in 8.1.1. Reject all needles not having flow rates of 190 to 210 ml./min. before sampling.

8.2 Calibration Curve. Dilute 50 ml. of the 1,000 μg NO_2/m^3 solution to 200 ml. with absorbing reagent. This solution contains 25 μg NO_2/m^3 . Pipet 1, 2, 5, and 15 ml. of the 25 μg NO_2/m^3 solution into 30-, 50-, 100- and 250-ml. volumetric flasks and dilute to the mark with absorbing reagent. The solution contains 150, 100, 125, and 130 μg NO_2/m^3 , respectively. Run standards as instructed in 7.2. Plot absorbance vs. μg NO_2/m^3 .

8.3 Epitomes. An overall average efficiency of 95 percent was obtained from test atmospheres having nitrogen dioxide concentrations of 140 $\mu\text{g}/\text{m}^3$ and 500 $\mu\text{g}/\text{m}^3$ by automated analysis (2).

9. Calculation.

9.1 Sampling.

9.1.1 Calculate volume of air sampled.

$$V = \frac{P_1 + P_2}{2} \times T \times 10^{-4}$$

V—Volume of air sampled, m.³

P₁—Measured flow rate before sampling, in.³/min.

- V_1 = Measured flow rate after sampling, ml./min.
 T = Time of sampling, min.
 10^{-6} = Conversion of ml. to m.³
 1.3 Calculate the concentration of nitrogen dioxide as $\mu\text{g. NO}_2/\text{m}^3$
 $\mu\text{g. NO}_2/\text{m}^3 = \frac{(\mu\text{g. NO}_2/\text{ml.}) \times 20}{V \times 0.35}$
 = $\frac{(\mu\text{g. NO}_2/\text{ml.}) \times 143}{V}$
 50 = Volume of absorbing reagent used in sampling, ml.
 V = Volume of air sampled, m.³
- 0.35 = Efficiency.
 9.21 If desired, concentration of nitrogen dioxide may be calculated as p.p.m. NO₂.
 $\text{p.p.m.} = (\mu\text{g. NO}_2/\text{m}^3) \times 5.22 \times 10^{-4}$
10. References.
 (1) Jacobs, M. R., and Hochheiser, S., "Continuous Sampling and Ultramicrodetermination of Nitrogen Dioxide in Air," *Anal. Chem.*, 30 425 (1958).
 (2) Purdie, L. J., Dudley, J. E., Clements, J. B., and Thompson, R. J., "Studies in Air Sampling for Nitrogen Dioxide," I. A reinvestigation of the Jacobs-Hochheiser Reagent. In Preparation.

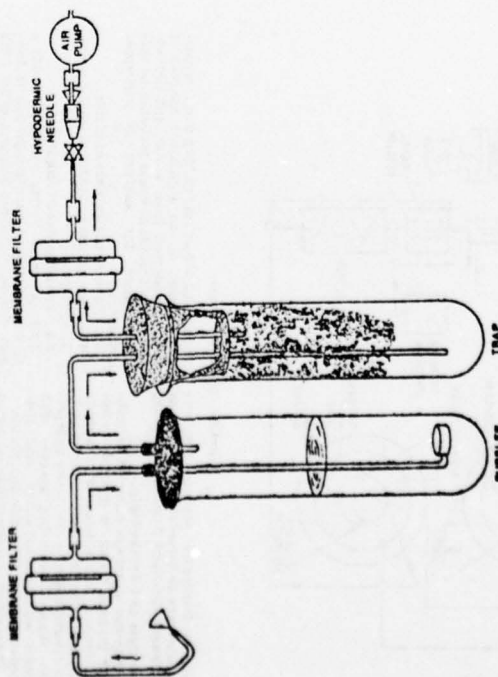


Figure F1. Sampling train.

APPENDIX II

AMBIENT AIR MONITORING REFERENCE
AND EQUIVALENT METHODS
(40 CFR 53)

- Sec.
53.4 Applications for reference or equivalent method determinations.
53.5 Processing of applications.
53.6 Right to witness conduct of tests.
53.7 Testing of methods at the initiative of the Administrator.
53.8 Designation of reference and equivalent methods.
53.9 Conditions of designation.
53.10 Appeal from a designation.
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53.12 Request for hearing on cancellation.
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53.14 Modification of a reference or equivalent method.
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53.16 Supersession of reference methods.
Subpart B—Procedures for Testing Performance Characteristics of Automated Methods
53.20 General provisions.
53.21 Test conditions.
53.22 Generation of test atmospheres.
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APPENDIX A—OPTIONAL FORMS FOR REPORTING TEST RESULTS

Subpart C—Procedures for Determining a Consistent Relationship Between Candidate Methods and Reference Methods

- 53.30 General provisions.
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53.32 Test procedures.

APPENDIX A—OPTIONAL FORM FOR REPORTING TEST RESULTS

AUTHORITY: Section 301(a) of the Clean Air Act (42 U.S.C. section 1857(a)), as amended by section 19(c)(2) of Public Law 91-604, 84 Stat. 1713.

SOURCE: 40 FR 7049, Feb. 18, 1975, unless otherwise noted.

Subpart A—General Provisions

§ 53.1 Definitions.

- (a) Terms used but not defined in this part shall have the meaning given them by the Act.
(b) "Act" means the Clean Air Act (42 U.S.C. 1857-1857i) as amended.
(c) "Agency" means the Environmental Protection Agency.
(d) "Administrator" means the Administrator of the Environmental Protection Agency or his authorized representative.
(e) "Reference method" means a method of sampling and analyzing the ambient air for an air pollutant that is specified as a reference method in an appendix to Part 50 of this chapter, or a method that has been designated as a

PART 53—AMBIENT AIR MONITORING REFERENCE AND EQUIVALENT METHODS

- Sec.
53.1 Definitions.
53.2 General requirements for a reference method determination.
53.3 General requirements for an equivalent method determination.

Subpart A—General Provisions

§ 53.2 Protection of Environment

reference method in accordance with this part; it does not include a method for which a reference method designation has been cancelled in accordance with § 53.11 or § 53.16.

(f) "Equivalent method" means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with this part; it does not include a method for which an equivalent method designation has been cancelled in accordance with § 53.11 or § 53.16.

(g) "Candidate method" means a method of sampling and analyzing the ambient air for an air pollutant for which an application for a reference method determination or an equivalent method determination is submitted in accordance with § 53.4, or a method tested at the initiative of the Administrator in accordance with § 53.7.

(h) "Manual method" means a method for measuring concentrations of an ambient air pollutant in which sample collection, analysis, or measurement, or some combination thereof, is performed manually.

(i) "Automated method" or "analyzer" means a method for measuring concentrations of an ambient air pollutant in which sample collection, analysis, and measurement are performed automatically.

(j) "Test analyzer" means an analyzer subjected to testing as a candidate method in accordance with Subpart B of this part, Subpart C of this part, or both.

(k) "Applicant" means a person who submits an application for a reference or equivalent method determination under § 53.4, or a person who assumes the rights and obligations of an applicant under § 53.7.

(l) "Ultimate purchaser" means the first person who purchases a reference method or an equivalent method for purposes other than resale.

[40 FR 7049, Feb. 18, 1975, as amended at 41 FR 11255, Mar. 17, 1976]

§ 53.2 General requirements for a reference method determination.

(a) *Manual methods.* Except as provided in § 53.16, manual methods will not be considered for reference method determinations under this part.

NOTE: As defined in § 53.1(e), "reference method" includes a manual method specified in an appendix to Part 50 of this chapter. Except as provided in § 53.16, the provisions

of this part are inapplicable to such a method.

(b) *Automated methods.* A candidate automated method must utilize the measurement principle and calibration procedures specified in the appropriate appendix to Part 50 of this chapter and meet the requirements specified in Subpart B of this part.

NOTE: Except as provided in § 53.16, an automated method will not be considered for a reference method determination if a manual reference method is specified in the appropriate appendix to Part 50 of this chapter.

[41 FR 11255, Mar. 17, 1976]

§ 53.3 General requirements for an equivalent method determination.

(a) *Manual methods.* Candidate manual methods must satisfy the requirements specified in Subpart C of this part.

(b) *Automated methods.* Candidate automated methods must satisfy the requirements specified in Subparts B and C of this part.

§ 53.4 Applications for reference or equivalent method determinations.

(a) Applications for reference or equivalent method determinations shall be submitted in triplicate to:

Director, Quality Assurance & Environmental Monitoring Laboratory, Department Z, United States Environmental Protection Agency, National Environmental Research Center, Research Triangle Park, North Carolina 27711.

(b) Each application shall be signed by an authorized representative of the applicant, shall be marked in accordance with § 53.15 (if applicable), and shall contain the following:

(1) A clear identification of the candidate method which will distinguish it from all other methods and by which it may be referred to unambiguously.

(2) A detailed description of the candidate method including but not limited to the following: The measurement principle, manufacturer, name, model number, and other forms of identification; a listing of the significant components; schematic diagrams; and a detailed description of the apparatus and measurement procedures.

(3) A copy of a comprehensive operation or instruction manual providing a complete and detailed description of the operational and calibration procedures prescribed for field use of the candidate method and all instruments utilized as

part of that method. The manual shall include adequate warning of potential safety hazards that may result from normal use, or (if the method is automated) from normal use or malfunction, of the method and a description of necessary safety precautions (see § 53.9(b)). For automated methods, the manual shall include a clear description of installation and operation procedures and of necessary periodic maintenance, as well as comprehensive trouble-shooting and corrective maintenance procedures and parts identification diagrams. The manual may be used to satisfy the requirements of paragraphs (b) (1) and (2) of this section to the extent that it includes information necessary to meet those requirements.

(4) A statement that the candidate method has been tested in accordance with the procedures described in Subpart B of this part, Subpart C of this part, or both, as applicable.

(5) Test data, records, calculations, and test results as specified in Subpart B of this part, Subpart C of this part, or both, as applicable.

(6) A statement that the method or analyzer tested in accordance with this part is representative of the candidate method described in the application.

(c) For candidate automated methods, the application shall also contain the following:

(1) A detailed description of the quality control program that will be utilized, if the candidate method is designated as a reference or equivalent method, to ensure that all analyzers offered for sale under that designation will have essentially the same performance characteristics as the analyzer tested in accordance with this part.

¹ Guidance for the development of such a manual may be found in the EPA report, (EPA 450/3-74-028) "Guideline specifications for the Development of Instruction Manuals for Automatic Air Monitoring Instruments," available from: National Technical Information Service, U.S. Department of Commerce, 6285 Port Royal Road, Springfield, Virginia 22151. (702-321-8543).

An example manual based on the above report and titled (EPA 450/3-74-028) "Fully Proceduralized Instruction Manual for the Bendix Ozone Monitor, Model 9007" is available from the same source.

(2) A description of the durability characteristics of such analyzers (see § 53.9(c)).

[40 FR 7049, Feb. 18, 1975, as amended at 40 FR 18168, Apr. 28, 1975]

§ 53.5 Processing of applications.

After receiving an application for a reference or equivalent method determination, the Administrator will publish notice of the application in the *Federal Register* and, within 75 calendar days after receipt of the application, take one or more of the following actions:

(a) Send notice to the applicant, in accordance with § 53.8, that the candidate method has been determined to be a reference or equivalent method;

(b) Send notice to the applicant that his application has been rejected, including a statement of reasons for rejection;

(c) Send notice to the applicant that additional information must be submitted before a determination can be made and specify the additional information that is needed (in such cases, the 75-day period shall commence upon receipt of the additional information);

(d) Send notice to the applicant that additional tests are necessary and specify what tests are necessary and how they shall be interpreted (in such cases, the 75-day period shall commence upon receipt of the additional test data); or

(e) Send notice to the applicant that additional tests will be conducted by the Administrator, specifying the nature of and reasons for the additional tests and the estimated time required (in such cases, the 75-day period shall commence 1 calendar day after the additional tests have been completed).

§ 53.6 Right to witness conduct of tests.

(a) Submission of an application for a reference or equivalent method determination shall constitute consent for the Administrator or his authorized representative, upon presentation of appropriate credentials, to witness or observe any tests required by this part in connection with the application or in connection with any modification or intended modification of the method by the applicant.

(b) The applicant shall have the right to witness or observe any test conducted by the Administrator in connection with the application or in connection with any modification or intended modification of the method by the applicant.

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(c) Any tests by either party that are to be witnessed or observed by the other party shall be conducted at a time and place mutually agreeable to both parties.

§ 53.7 Testing of methods at the initiative of the Administrator.

(a) In the absence of an application for a reference or equivalent method determination, the Administrator may conduct the tests required by this part for such a determination, may compile such other information as may be necessary in his judgment to make such a determination, and (c) the basis of the tests and information may determine that a method satisfies applicable requirements of this part.

(b) In the absence of an application requesting the Administrator to consider revising an appendix to Part 50 of this chapter in accordance with § 53.16, the Administrator may conduct such tests and compile such information as may be necessary in his judgment to make a determination under § 53.16(d) and on the basis of the tests and information make such a determination.

(c) If a method tested in accordance with this section is designated as a reference or equivalent method in accordance with § 53.8 or is specified or designated as a reference method in accordance with § 53.16, any person who offers the method for sale as a reference or equivalent method thereafter shall assume the rights and obligations of an applicant for purposes of this part with the exception of those pertaining to submission and processing of applications. [40 FR 7049, Feb. 18, 1975, as amended at 41 FR 11256, Mar. 17, 1976]

§ 53.8 Designation of reference and equivalent methods.

(a) A candidate method determined by the Administrator to satisfy the applicable requirements of this part shall be designated as a reference method or equivalent method (as applicable), and a notice of the designation shall be submitted for publication in the *Federal Register* not later than 15 days after the determination is made.

(b) A notice indicating that the method has been determined to be a reference method or an equivalent method shall be sent to the applicant. This notice shall constitute proof of the determination until a notice of designation is published in accordance with paragraph (a) of this section.

(c) The Administrator will maintain a current list of methods designated as reference or equivalent methods in accordance with this part and will send a copy of the list to any person or group upon request. A copy of the list will be available for inspection or copying at EPA Regional Offices.

§ 53.9 Conditions of designation.

Designation of a candidate method as a reference method or equivalent method shall be conditioned on the applicant's compliance with the following requirements. Failure to comply with any of the requirements shall constitute a ground for cancellation of the designation in accordance with § 53.11.

(a) Any method offered for sale as a reference or equivalent method shall be accompanied by a copy of the manual referred to in § 53.4(b)(3) when delivered to any ultimate purchaser.

(b) Any method offered for sale as a reference or equivalent method shall generate no unreasonable hazard to operators or to the environment during normal use or (if the method is automated) during normal use or when malfunctioning.

(c) Any analyzer offered for sale as a reference or equivalent method shall function within the limits of the performance specifications referred to in § 53.20(a) for at least 1 year after delivery and acceptance when maintained and operated in accordance with the manual referred to in § 53.4(b)(3).

(d) Any analyzer offered for sale as a reference or equivalent method shall bear a prominent, permanently affixed label or sticker indicating that the analyzer has been designated by EPA as a reference method or as an equivalent method (as applicable) in accordance with this part.

(e) If an analyzer is offered for sale as a reference or equivalent method but has one or more selectable ranges, the label or sticker required by paragraph (d) of this section shall be placed in close proximity to the range selector and shall indicate clearly which range or ranges have been designated as parts of the reference or equivalent method.

(f) An applicant who offers analyzers for sale as reference or equivalent methods shall maintain an accurate and current list of the names and mailing addresses of all ultimate purchasers of such analyzers. For a period of seven years after publication of the reference

or equivalent method designation applicable to such an analyzer, the applicant shall notify all ultimate purchasers of the analyzer within 30 days if the designation has been cancelled in accordance with § 53.11 or § 53.16 or if adjustment of the analyzer is necessary under § 53.11(b).

(g) If an applicant modifies an analyzer that has been designated as a reference or equivalent method, the applicant shall not sell the analyzer as modified as a reference or equivalent method nor attach a label or sticker to the analyzer as modified under paragraph (d) or (e) of this section until he has received notice under § 53.14(c) that the existing designation or a new designation will apply to the analyzer as modified or has applied for and received notice under § 53.8(b) of a new reference or equivalent method determination for the analyzer as modified.

[40 FR 7049, Feb. 18, 1975, as amended at 41 FR 11256, Mar. 17, 1976]

§ 53.10 Appeal from rejection of application.

Any applicant whose application for a reference or equivalent method determination has been rejected may appeal the Administrator's decision by taking one or more of the following actions:

- The applicant may submit new or additional information in support of the application.
- The applicant may request that the Administrator reconsider the data and information already submitted.
- The applicant may request that any test conducted by the Administrator that was a material factor in his decision to reject the application be repeated.

§ 53.11 Cancellation of reference or equivalent method designation.

(a) *Preliminary finding.* If the Administrator makes a preliminary finding on the basis of any information available to him that a representative sample of a method designated as a reference or equivalent method and offered for sale as such does not fully satisfy the requirements of this part or that there is any violation of the requirements set forth in § 53.9, he may initiate proceedings to cancel the designation in accordance with the following procedures.

- Notification and opportunity to demonstrate or achieve compliance.* (1) After making a preliminary finding in accordance with paragraph (a) of this

section, the Administrator will send notice of the preliminary finding to the applicant, together with a statement of the facts and reasons on which the preliminary finding is based, and will publish notice of the preliminary finding in the FEDERAL REGISTER.

(2) The applicant will be afforded an opportunity to demonstrate or to achieve compliance with the requirements of this part within 60 days after publication of notice in accordance with paragraph (b) (1) of this section or within such further period as the Administrator may allow by demonstrating to the satisfaction of the Administrator that the method in question satisfies the requirements of this part, by commencing a program to make any adjustments that are necessary to bring the method into compliance, or by taking such action as may be necessary to cure any violation of the requirements of § 53.9. If adjustments are necessary to bring the method into compliance, all such adjustments shall be made within a reasonable time as determined by the Administrator. If the applicant demonstrates or achieves compliance in accordance with this paragraph (b) (2), the Administrator will publish notice of such demonstration or achievement in the FEDERAL REGISTER.

(c) *Request for hearing.* Within 60 days after publication of notice in accordance with paragraph (b) (1) of this section, the applicant or any interested person may request a hearing as provided in § 53.12.

(d) *Notice of cancellation.* If, at the end of the period referred to in paragraph (b) (2) of this section, the Administrator determines that the reference or equivalent method designation should be cancelled, he will publish a notice of cancellation in the FEDERAL REGISTER and delete the designation from the list maintained under § 53.8(c). If a hearing has been requested and granted in accordance with § 53.12, action under this paragraph (d) will be taken only after completion of proceedings (including any administrative review) conducted in accordance with § 53.13 and only if the decision of the Administrator reached in such proceedings is that the designation in question should be cancelled.

§ 53.12 Request for hearing on cancellation.

Within 60 days after publication of notice in accordance with § 53.11(b) (1),

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the applicant or any interested person may request a hearing on the Administrator's action. The request shall be in writing, signed by an authorized representative of the applicant or interested person, and shall include a statement specifying (a) any objections to the Administrator's action and (b) data or other information in support of such objections. If, after reviewing the request and supporting data, the Administrator finds that the request raises a substantial issue of fact, he will grant a hearing in accordance with § 53.13 with respect to such issue.

§ 53.13 Hearings.

(a) (1) After granting a request for a hearing under § 53.12, the Administrator will designate a presiding officer for the hearing.

(2) If a time and place for the hearing have not been fixed by the Administrator, the hearing will be held as soon as practicable at a time and place fixed by the presiding officer, except that the hearing shall in no case be held sooner than 30 days after publication of a notice of hearing in the FEDERAL REGISTER.

(3) For purposes of the hearing, the parties shall include the Environmental Protection Agency, the applicant or interested person(s) who requested the hearing, and any person permitted to intervene in accordance with paragraph (c) of this section.

(4) The Deputy General Counsel or his representative will represent the Environmental Protection Agency in any hearing under this section.

(5) Each party other than the Environmental Protection Agency may be represented by counsel or by any other duly authorized representative.

(b) (1) Upon his appointment, the presiding officer will establish a hearing file. The file shall contain copies of the notices issued by the Administrator pursuant to § 53.11(b) (1), together with any accompanying material, the request for a hearing and supporting data submitted therewith, the notice of hearing published in accordance with paragraph (a) (2) of this section, and correspondence and other material data relevant to the hearing.

(2) The hearing file shall be available for inspection by the parties or their representatives at the office of the presiding officer, except to the extent that it contains information identified in accordance with § 53.15.

(c) At his discretion, the presiding officer may permit any interested person to intervene in the hearing upon such a showing of interest as the presiding officer may require; provided that leave to intervene may be denied in the interest of expediting the hearing where it appears that the interests of the person seeking to intervene will be adequately represented by another party (or by other parties), including the Environmental Protection Agency.

(d) (1) The presiding officer, upon the request of any party or at his discretion, may arrange for a prehearing conference at a time and place specified by him to consider the following:

- Simplification of the issues.
- Stipulations, admissions of fact, and the introduction of documents.
- Limitation of the number of expert witnesses.

(iv) Possibility of agreement disposing of all or any of the issues in dispute.

(v) Such other matters as may aid in the disposition of the hearing, including such additional tests as may be agreed upon by the parties.

(2) The results of the conference shall be reduced to writing by the presiding officer and made part of the record.

(e) (1) Hearings shall be conducted by the presiding officer in an informal but orderly and expeditious manner. The parties may offer oral or written evidence, subject to exclusion by the presiding officer of irrelevant, immaterial, or repetitious evidence.

(2) Witnesses shall be placed under oath.

(3) Any witness may be examined or cross-examined by the presiding officer, the parties, or their representatives. The presiding officer may, at his discretion, limit cross-examination to relevant and material issues.

(4) Hearings shall be reported verbatim. Copies of transcripts of proceedings may be purchased from the reporter.

(5) All written statements, charts, tabulations, and data offered in evidence at the hearing shall, upon a showing satisfactory to the presiding officer of their authenticity, relevancy, and materiality, be received in evidence and shall constitute part of the record.

(6) Oral argument shall be permitted. The presiding officer may limit oral presentations to relevant and material issues and designate the amount of time allowed for oral argument.

(f) (1) The presiding officer shall make an initial decision which shall include written findings and conclusions and the reasons therefor on all the material issues of fact, law, or discretion presented on the record. The findings, conclusions, and written decision shall be provided to the parties and made part of the record. The initial decision shall become the decision of the Administrator without further proceedings unless there is an appeal to, or review on motion of, the Administrator within 30-calendar days after the initial decision is filed.

(2) On appeal from or review of the initial decision, the Administrator will have all the powers which he would have in making the initial decision, including the discretion to require or allow briefs, oral argument, the taking of additional evidence, or the remanding to the presiding officer for additional proceedings. The decision by the Administrator will include written findings and conclusions and the reasons or basis therefor on all the material issues of fact, law, or discretion presented on the appeal or considered in the review.

§ 53.14 Modification of a reference or equivalent method.

(a) An applicant who offers a method for sale as a reference or equivalent method shall report any intended modification of the method, including but not limited to modifications of design or construction or of operational and maintenance procedures specified in the operation manual, to the Administrator prior to implementation of the modification (see § 53.9(g)). The report shall be signed by an authorized representative of the applicant, marked in accordance with § 53.15 (if applicable), and addressed as specified in § 53.4(a).

(b) A report submitted under paragraph (a) of this section shall include: (1) A description, in such detail as may be appropriate, of the intended modification;

(2) A brief statement of the applicant's belief that the modification will, will not, or may affect the performance characteristics of the method;

(3) If the applicant believes the modification will or may affect the performance characteristics of the method, a brief statement of the probable effect; and

(4) Such further information, including test data, as may be necessary to explain and support any statement required

by paragraphs (b) (2) and (b) (3) of this section.

(c) Within 30-calendar days after receiving a report under paragraph (a) of this section, the Administrator will take one or more of the following actions:

(1) Notify the applicant that the designation will continue to apply to the method if the modification is implemented.

(2) Send notice to the applicant that a new designation will apply to the method (as modified) if the modification is implemented, submit notice of the determination for publication in the FEDERAL REGISTER, and revise or supplement the list referred to in § 53.8(c) to reflect the determination.

(3) Send notice to the applicant that the designation will not apply to the method (as modified) if the modification is implemented and submit notice of the determination for publication in the FEDERAL REGISTER.

(4) Send notice to the applicant that additional information must be submitted before a determination can be made and specify the additional information that is needed (in such cases, the 30-day period shall commence upon receipt of the additional information).

(5) Send notice to the applicant that additional tests are necessary and specify what tests are necessary and how they shall be interpreted (in such cases, the 30-day period shall commence upon receipt of the additional test data); or

(6) Send notice to the applicant that additional tests will be conducted by the Administrator and specify the reasons for and the nature of the additional tests (in such cases, the 30-day period shall commence one calendar day after the additional tests are completed).

(d) An applicant who has received a notice under paragraph (c) (3) of this section may appeal the Administrator's action as follows:

(1) The applicant may submit new or additional information pertinent to the intended modification.

(2) The applicant may request the Administrator to reconsider data and information already submitted.

(3) The applicant may request that the Administrator repeat any test he conducted that was a material factor in his determination. A representative of

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the applicant may be present during the performance of any such test.

(40 FR 7049, Feb. 18, 1975, as amended at 40 FR 18108, Apr. 25, 1976; 41 FR 11266, Mar. 17, 1976)

§ 53.15 Trade secrets and confidential or privileged information.

Any information submitted under this part that is claimed to be a trade secret or confidential or privileged information shall be marked or otherwise clearly identified as such in the submittal. Information so identified will be treated in accordance with Part 2 of this chapter concerning public information).

§ 53.16 Supersession of reference method.

(a) This section prescribes procedures and criteria applicable to requests that the Administrator specify a new reference method, or a new measurement principle and calibration procedure on which reference methods shall be based, by revision of the appropriate appendix to Part 50 of this chapter. Such action will ordinarily be taken only if the Administrator determines that a candidate method or a variation thereof is substantially superior to the existing reference method(s).

(b) In exercising his discretion under this section, the Administrator will consider: (1) The benefits, in terms of the requirements and purposes of the Act, that would result from specifying a new reference method or a new measurement principle and calibration procedure; (2) the potential economic consequences of such action for State and local control agencies; and (3) any disruption of State and local air quality monitoring programs that might result from such action.

(c) An applicant who wishes the Administrator to consider revising an appendix to Part 50 of this chapter on the ground that the applicant's candidate method is substantially superior to the existing reference method(s) shall submit an application for a reference or equivalent method determination in accordance with § 53.4 and shall indicate therein that he desires such consideration. The application shall include, in addition to the information required by § 53.4, data and any other information supporting the applicant's claim that the candidate method is substantially superior to the existing reference method(s).

(d) After receiving an application under paragraph (c) of this section, the

Administrator will publish notice of its receipt in the FEDERAL REGISTER and, within 75 calendar days after receipt of the application, take one of the following actions:

(1) Determine that it is appropriate to propose a revision of the appendix in question and send notice of the determination to the applicant;

(2) Determine that it is inappropriate to propose a revision of the appendix in question, determine whether the candidate method is a reference or equivalent method, and send notice of the determination, including a statement of reasons for the determination not to propose a revision, to the applicant;

(3) Send notice to the applicant that additional information must be submitted before a determination can be made and specify the additional information that is needed (in such cases, the 75-day period shall commence upon receipt of the additional information); or

(4) Send notice to the applicant that additional tests are necessary, specifying what tests are necessary and how they shall be interpreted (in such cases, the 75-day period shall commence upon receipt of the additional test data); or

(5) Send notice to the applicant that additional tests will be conducted by the Administrator, specifying the nature of and reasons for the additional tests and the estimated time required (in such cases, the 75-day period shall commence one calendar day after the additional tests have been completed).

(e) (1) After making a determination under paragraph (d) (1) of this section, the Administrator will publish a notice of proposed rulemaking in the FEDERAL REGISTER. The notice will indicate that the Administrator proposes (i) to revise the appendix in question; (ii) where the appendix specifies a measurement principle and calibration procedure, to cancel the reference method designations based on the appendix; and (iii) to cancel equivalent method designations based on the existing reference method(s). The notice will include the terms or substance of the proposed revision, will indicate what period(s) of time the Administrator proposes to allow for replacement of existing methods under § 51.17(a) (4) of this chapter, and will solicit public comments on the proposal with particular reference to the considerations set forth in paragraphs (a) and (b) of this section.

(2) If, after consideration of comments received, the Administrator deter-

mines that the appendix in question should be revised, he will by publication in the FEDERAL REGISTER (1) promulgate the proposed revision, with such modifications as may be appropriate in view of comments received; (ii) where the appendix (prior to revision) specifies a measurement principle and calibration procedure, cancel reference method designations based on the appendix; (iii) cancel equivalent method designations based on the existing reference method(s); and (iv) specify the period(s) that will be allowed for replacement of existing methods under § 53.17(a)(4) of this chapter, with such modifications from the proposed period(s) as may be appropriate in view of comments received. Cancelled designations will be deleted from the list maintained under § 53.8(c). The requirements and procedures for cancellation set forth in § 53.11 shall be inapplicable to cancellation of reference or equivalent method designations under this section.

(3) If the appendix in question is revised to specify a new measurement principle and calibration procedure on which the applicant's candidate method is based, the Administrator will take appropriate action under § 53.5 to determine whether the candidate method is a reference method.

(4) Upon taking action under paragraph (e)(2) of this section, the Administrator will send notice of the action to all applicants for whose methods reference and equivalent method designations are cancelled by such action.

(f) An applicant who has received notice of a determination under paragraph (d) (2) of this section may appeal the determination by taking one or more of the following actions:

(1) The applicant may submit new or additional information in support of the application.

(2) The applicant may request that the Administrator reconsider the data and information already submitted.

(3) The applicant may request that any test conducted by the Administrator that was a material factor in making the determination be repeated.

[41 FR 11296, Mar. 17, 1976]

Subpart B—Procedures for Testing Performance Characteristics of Automated Methods

§ 53.20 General provisions.

(a) The test procedures given in this subpart shall be used to test the per-

formance of candidate automated methods against the performance specifications given in Table B-1. A test analyzer representative of the candidate automated method must exhibit performance better than, or equal to, the specified value for each such specification (except Range) to satisfy the requirements of this subpart. Except as provided in paragraph (b) of this section, the range of the candidate method must be the range specified in Table B-1 to satisfy the requirements of this subpart.

(b) For a candidate method having more than one selectable range, one range must be that specified in Table B-1 and a test analyzer representative of the method must pass the tests required by this subpart while operated in that range. The tests may be repeated for a broader range (i.e., one extending to higher concentrations) than that specified in Table B-1 provided that the range does not extend to concentrations more than two times the upper range limit specified in Table B-1. If the application is for a reference method determination, the tests may be repeated for a narrower range (one extending to lower concentrations) than that specified in Table B-1.

If the tests are conducted or passed only for the specified range, any reference or equivalent method determination with respect to the method will be limited to that range. If the tests are passed for both the specified range and a broader range (or ranges), any such determination will include the broader range(s) as well as the specified range, provided that the tests required by Subpart C of this part (if applicable) are met for the broader range(s). If the tests are passed for both the specified range and a narrower range, a reference method determination for the method will include the narrower range as well as the specified range. Appropriate test data shall be submitted for each range sought to be included in a reference or equivalent method determination under this paragraph (b).

(c) For each performance specification (except Range), the test procedure shall be initially repeated seven (7) times to yield 7 test results. Each result shall be compared with the corresponding specification in Table B-1; a value higher than or outside that specified constitutes a failure. These 7 results for each parameter shall be interpreted as follows:

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(1) Zero (0) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

TABLE B-1. PERFORMANCE SPECIFICATIONS FOR AUTOMATED METHODS

Performance parameter	Units ¹	Bulmer dioxide	Oxidants monoxide	Carbon monoxide	Definitions and test procedures
1. Range	Parts per million	0-0.5	0-0.5	0-0.5	§ 53.21(a)
2. Noise	do	0.05	0.05	0.05	§ 53.21(b)
3. Lower detectable limit	do	0.01	0.01	0.01	§ 53.21(c)
4. Interference Equivalent	do	±0.02	±0.02	±0.02	§ 53.21(d)
5. Total Interference	do	±0.02	±0.02	±0.02	§ 53.21(e)
6. Zero drift, 12 and 24 hr.	do	±0.02	±0.02	±0.02	§ 53.21(f)
7. Span drift, 24 hours	Percent	±2.0	±2.0	±2.0	§ 53.21(g)
8. Linearity	Percent	±2.0	±2.0	±2.0	§ 53.21(h)
9. 50 percent of upper range limit	Minutes	20	20	20	§ 53.21(i)
10. Precision	do	15	15	15	§ 53.21(j)
11. Rise time	do	15	15	15	§ 53.21(k)
12. Fall time	do	15	15	15	§ 53.21(l)
13. Reproducibility	do	15	15	15	§ 53.21(m)
14. Drift	do	15	15	15	§ 53.21(n)
15. Response time	do	15	15	15	§ 53.21(o)
16. Recovery time	do	15	15	15	§ 53.21(p)
17. Storage stability	do	15	15	15	§ 53.21(q)
18. Transportability	do	15	15	15	§ 53.21(r)
19. Reliability	do	15	15	15	§ 53.21(s)
20. Safety	do	15	15	15	§ 53.21(t)
21. Maintenance	do	15	15	15	§ 53.21(u)
22. Calibration	do	15	15	15	§ 53.21(v)
23. Documentation	do	15	15	15	§ 53.21(w)
24. Reporting	do	15	15	15	§ 53.21(x)
25. Archiving	do	15	15	15	§ 53.21(y)
26. Retrieval	do	15	15	15	§ 53.21(z)
27. Destruction	do	15	15	15	§ 53.21(aa)
28. Backup	do	15	15	15	§ 53.21(ab)
29. Restoration	do	15	15	15	§ 53.21(ac)
30. Security	do	15	15	15	§ 53.21(ad)
31. Access	do	15	15	15	§ 53.21(ae)
32. Audit	do	15	15	15	§ 53.21(af)
33. Accountability	do	15	15	15	§ 53.21(ag)
34. Transparency	do	15	15	15	§ 53.21(ah)
35. Integrity	do	15	15	15	§ 53.21(ai)
36. Confidentiality	do	15	15	15	§ 53.21(aj)
37. Privacy	do	15	15	15	§ 53.21(ak)
38. Data protection	do	15	15	15	§ 53.21(al)
39. Information security	do	15	15	15	§ 53.21(am)
40. Risk management	do	15	15	15	§ 53.21(an)
41. Business continuity	do	15	15	15	§ 53.21(ao)
42. Disaster recovery	do	15	15	15	§ 53.21(ap)
43. Incident response	do	15	15	15	§ 53.21(aq)
44. Crisis management	do	15	15	15	§ 53.21(ar)
45. Communication	do	15	15	15	§ 53.21(as)
46. Public relations	do	15	15	15	§ 53.21(at)
47. Media relations	do	15	15	15	§ 53.21(au)
48. Stakeholder relations	do	15	15	15	§ 53.21(av)
49. Investor relations	do	15	15	15	§ 53.21(aw)
50. Supplier relations	do	15	15	15	§ 53.21(ax)
51. Customer relations	do	15	15	15	§ 53.21(ay)
52. Employee relations	do	15	15	15	§ 53.21(az)
53. Community relations	do	15	15	15	§ 53.21(ba)
54. Government relations	do	15	15	15	§ 53.21(bb)
55. Regulatory relations	do	15	15	15	§ 53.21(bc)
56. Industry relations	do	15	15	15	§ 53.21(bd)
57. Academic relations	do	15	15	15	§ 53.21(be)
58. Non-profit relations	do	15	15	15	§ 53.21(bf)
59. Media relations	do	15	15	15	§ 53.21(bg)
60. Public relations	do	15	15	15	§ 53.21(bh)
61. Media relations	do	15	15	15	§ 53.21(bi)
62. Public relations	do	15	15	15	§ 53.21(bj)
63. Media relations	do	15	15	15	§ 53.21(bk)
64. Public relations	do	15	15	15	§ 53.21(bl)
65. Media relations	do	15	15	15	§ 53.21(bm)
66. Public relations	do	15	15	15	§ 53.21(bn)
67. Media relations	do	15	15	15	§ 53.21(bo)
68. Public relations	do	15	15	15	§ 53.21(bp)
69. Media relations	do	15	15	15	§ 53.21(bq)
70. Public relations	do	15	15	15	§ 53.21(br)
71. Media relations	do	15	15	15	§ 53.21(bs)
72. Public relations	do	15	15	15	§ 53.21(bt)
73. Media relations	do	15	15	15	§ 53.21(bu)
74. Public relations	do	15	15	15	§ 53.21(bv)
75. Media relations	do	15	15	15	§ 53.21(bw)
76. Public relations	do	15	15	15	§ 53.21(bx)
77. Media relations	do	15	15	15	§ 53.21(by)
78. Public relations	do	15	15	15	§ 53.21(bz)
79. Media relations	do	15	15	15	§ 53.21(ca)
80. Public relations	do	15	15	15	§ 53.21(cb)
81. Media relations	do	15	15	15	§ 53.21(cc)
82. Public relations	do	15	15	15	§ 53.21(cd)
83. Media relations	do	15	15	15	§ 53.21(ce)
84. Public relations	do	15	15	15	§ 53.21(cf)
85. Media relations	do	15	15	15	§ 53.21(cf)
86. Public relations	do	15	15	15	§ 53.21(cf)
87. Media relations	do	15	15	15	§ 53.21(cf)
88. Public relations	do	15	15	15	§ 53.21(cf)
89. Media relations	do	15	15	15	§ 53.21(cf)
90. Public relations	do	15	15	15	§ 53.21(cf)
91. Media relations	do	15	15	15	§ 53.21(cf)
92. Public relations	do	15	15	15	§ 53.21(cf)
93. Media relations	do	15	15	15	§ 53.21(cf)
94. Public relations	do	15	15	15	§ 53.21(cf)
95. Media relations	do	15	15	15	§ 53.21(cf)
96. Public relations	do	15	15	15	§ 53.21(cf)
97. Media relations	do	15	15	15	§ 53.21(cf)
98. Public relations	do	15	15	15	§ 53.21(cf)
99. Media relations	do	15	15	15	§ 53.21(cf)
100. Public relations	do	15	15	15	§ 53.21(cf)

¹ To convert from parts per million to microgram per cubic meter at 25° C and 760 mm Hg, multiply by M/O.0047, where M is the molecular weight of the gas.

(d) The tests for zero drift, span drift, lag time, rise time, fall time, and pre-

cedural shall be combined into a single sequential procedure to be conducted at various line voltages and ambient temperatures specified in § 53.23(e). The tests for noise, lower detectable limit, and interference equivalents shall be made at any temperature between 20° C and 30° C and at any normal line voltage between 105 and 125 volts, and shall be conducted such that not more than three (3) test results for each parameter are obtained per 24 hours.

(e) All response readings to be recorded shall first be converted to concentration units according to the calibration curve constructed in accordance with § 53.21(b). (1) All recorder chart tracings, records, test data and other documentation obtained from or pertinent to these tests shall be identified, dated, signed by the analyst performing the test, and submitted.

(2) For each performance specification (except Range), the test procedure shall be initially repeated seven (7) times to yield 7 test results. Each result shall be compared with the corresponding specification in Table B-1; a value higher than or outside that specified constitutes a failure. These 7 results for each parameter shall be interpreted as follows:

(1) Zero (0) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

(1) One (1) or two (2) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a

zero capability, adjust either the control of the test analyzer or the chart recorder to obtain a +5% offset zero reading on the recorder chart to facilitate observing negative response or drift. If the calibration method is not capable of negative response, the test analyzer (not recorder) shall be operated with an offset zero. Construct and submit a calibration curve showing a plot of recorder scale readings (ordinate) against pollutant concentrations (abscissa). A plot of output units (volts, millivolts, milliamperes, etc.) against pollutant concentrations shall also be determined for methods not including an integral chart recorder. All such plots shall consist of at least seven (7) approximately equally spaced, identifiable points, including 0 and 90 ± 5 percent of full scale.

(c) Once the test analyzer has been set up and calibrated and the tests started, manual adjustment or normal periodic maintenance is permitted only every 3 days. Automatic adjustments which the test analyzer performs by itself are permitted at any time. The submitted records shall show clearly when any manual adjustment or periodic maintenance was made and describe the operations performed.

(d) If the test analyzer should malfunction during any of the performance tests, the tests for that parameter shall be repeated. A detailed explanation of the malfunction, remedial action taken, and whether recalibration was necessary (along with all pertinent records and charts) shall be submitted. If more than

one malfunction occurs, all performance test procedures for all parameters shall be repeated.

(e) Tests for all performance parameters shall be completed on the same test analyzer, except that use of multiple test analyzers to accelerate testing will be permitted when alternate ranges of a multi-range candidate method are being tested.

§ 53.22 Generation of test atmospheres.

(a) Table B-2 specifies preferred methods for generating test atmospheres and suggested methods of verifying the concentrations. Only one means of establishing the concentration of a test atmosphere is normally required. If the method of generation can produce reproducible concentrations, verification is optional. If the method of generation is not reproducible, then establishment of the concentration by some verification method is required. However, when a method of generation other than that given in Table B-2 is used, the test concentration shall be verified.

(b) The test atmosphere delivery system shall be designed and constructed so as not to significantly alter the test atmosphere composition or concentration during the period of the test. The delivery system shall be fabricated from borosilicate glass or FEP Teflon.

(c) The output of the test atmosphere generation system shall be sufficiently stable to obtain stable response during the required tests. If a permeation device is used for generation of a test atmosphere, the device, as well as the air passing over it, shall be controlled to $\pm 0.1^\circ \text{C}$.

TABLE B-2. TEST ATMOSPHERES

Test gas	Generation	Verification
Ammonia	Permeation device similar to system described in references 1 and 2.	Isopropyl alcohol method, reference 3.
Carbon dioxide	Cylinder of zero air or nitrogen containing CO ₂ as specified in table B-3.	See NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are certified to be accurate and submit to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.
Carbon monoxide	Cylinder of zero air or nitrogen containing CO as required to obtain the concentration specified in table B-3.	Collect samples in bubbler containing distilled water and analyze by the standard method, ASTM (D319), p. 25, reference 4.
Ethane	Cylinder of zero air or nitrogen containing ethane as required to obtain the concentration specified in table B-3.	See NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are certified to be accurate and submit to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.
Ethylene	Cylinder of zero air or nitrogen containing ethylene as required to obtain the concentration specified in table B-3.	See NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are certified to be accurate and submit to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.
Hydrogen chloride	Cylinder of zero air or nitrogen containing hydrogen chloride as required to obtain the concentration specified in table B-3.	See NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are certified to be accurate and submit to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.
Hydrogen sulfide	Permeation device system described in references 1 and 2.	See NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are certified to be accurate and submit to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.

Use NBS-certified standards whenever possible. If NBS standards are not available, obtain 2 standards from independent sources which agree within 2 percent; or obtain one standard and submit it to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.

Collect samples in bubbler containing distilled water and analyze by the mercuric thiocyanate method, ASTM (D512), p. 29, reference 4.

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TABLE B-2. TEST A MOSPHERES--Continued

Test gas	Generation	Verification
Methane.....	Cylinder of zero air containing methane as required to obtain the concentration specified in table B-3.	Use NBS-certified standards whenever possible. If NBS standards are not available, obtain 7 standards from independent sources with a spread within 2 percent; or obtain one standard and submit it to an independent laboratory for analysis which must agree within 2 percent.
Nitric acids.....	Cylinder 1 of compressed nitrogen containing approximately 100 ppm NO ₂ . Dilute with zero air to required concentration.	Gas-phase titration as described in reference 6, section 7.1.
Nitrogen dioxide.....	1. Permeation device, similar to system described in references 1 and 2. Cylinder 2, appendix D, as described in reference 1, appendix D.	1. Use an NO _x analyzer calibrated with a gravimetrically calibrated permeation device. 2. Use an NO _x analyzer calibrated by gas-phase titration of an analyzer calibrated by gas-phase titration as described in reference 6, section 7.1.
Ozone.....	Permeation device. Similar to system described in reference method for SO ₂ , reference 4, appendix B.	1. Use an ozone analyzer calibrated by gas-phase titration as described in reference 6, section 7.1. 2. Use an ozone analyzer calibrated by gas-phase titration as described in reference 6, section 7.1.
Sulfur dioxide.....	Permeation device. Similar to system described in reference method for SO ₂ , reference 4, appendix B.	1. Use an SO ₂ analyzer calibrated with a gravimetrically calibrated permeation device. 2. Use an SO ₂ analyzer calibrated by gas-phase titration of an analyzer calibrated by gas-phase titration as described in reference 6, section 7.1.
Water.....	Pass zero air through distilled water at a fixed known temperature between 20° and 30° C. until the air from the bottom of the container is saturated with water at the concentration specified in table B-3.	Measure relative humidity by means of a dew-point indicator, calibrated electrolytic or psychrometric hygrometer, or wet/dry bulb thermometer.
Xenon.....	Cylinder of prepurified nitrogen containing 100 ppm xenon. Dilute with zero air to concentration specified in table B-3.	Use NBS-certified standards whenever possible. If NBS standards are not available, obtain 7 standards from independent sources with a spread within 2 percent; or obtain one standard and submit it to an independent laboratory for analysis which must agree within 2 percent.
Zero air.....	1. Ambient air purified by appropriate scrubbers or other devices such that it is free of contaminants known to cause a detectable response on the analyzer. 2. Cylinder of compressed zero air certified by the supplier or an independent laboratory to be free of contaminants known to cause a detectable response on the analyzer.	Use NBS-certified standards whenever possible. If NBS standards are not available, obtain 7 standards from independent sources with a spread within 2 percent; or obtain one standard and submit it to an independent laboratory for analysis which must agree within 2 percent of the supplier's nominal analysis.

1. The standard test pressure regulator dedicated to the pollutant measured.

References: A. E., and Orttman, G. C., "Primary Standards for Trace Gas Analysis," *Anal. Chem.* 38, 1966, 1969.

Reference 2: Seagriffell, F. P., A. E., Rosenburg, Z., and Bell, J. P., "Primary Standards for Trace Gas Analysis," *Anal. Chem.* 38, 1966, 1969.

Reference 3: "Tentative Method of Analysis for Ammonia in the Atmosphere (Indophenol Method)," *Health Lab. Science*, vol. 10, No. 2, 135-138, April 1973.

Reference 4: 1973 Annual Book of ASTM Standards, American Society for Testing and Materials, 1918 Race St., Philadelphia, 1973.

Reference 5: *Methods for Air Sampling and Analysis*, Interagency Committee, 1972, American Public Health Association, 1015.

Reference 6: *Federal Register*, vol. 38, No. 110, Tentative Method for the Continuous Measurement of Nitrogen Dioxide (Chemiluminescent Method), 1973, National Air Quality Standards Administration, 400 M Street, N.W., Washington, D.C. 20560.

Reference 7: *Federal Register*, vol. 38, No. 228, National Primary and Secondary Ambient Air Quality Standards, 1973, 205, 1971.

(d) All diluent air shall be zero air free of contaminants likely to cause a detectable response on the test analyzer.

(e) The concentration of each test

atmosphere shall be established and/or

verified before or during each series of

tests. Samples for verifying test concen-

trations shall be collected from the test

atmosphere delivery system as close as possible to the sample intake port of the

possible to the sample intake port of the test analyzer.

(f) The accuracy of all flow measurements.

(1) The accuracy of all flow measurements used to calculate test atmosphere

concentrations shall be documented and

connections shall be documented and referenced to a primary standard (such

as a spirometer, bubble meter, etc.). Any

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conditions which a method is capable of measuring.

Note.—The nominal range is specified as the lower limit, upper range limits in concentration units, for example, 0–0.5 p.p.m.

(2) **Test Procedure.** Submit a suitable calibration curve, as specified in § 53.21 (b), showing the test analyzer's response over at least 95 percent of the required range.

Note.—A single calibration curve will normally suffice.

(b) **Noise.**—(1) **Technical Definition.** Spontaneous, short duration deviations in output, about the mean output, which are not caused by input concentration changes. Noise is determined as the standard deviation about the mean and is expressed in concentration units.

(2) **Test Procedure.** (i) Allow sufficient time for the test analyzer to warm up and stabilize. Determine at two concentrations, first using zero air and then a pollutant test gas concentration as indicated below. The noise specification in Table B-1 shall apply to both of these tests.

(ii) Connect an integrating-type digital meter (DM) suitable for the test analyzer's output and accurate to three significant digits, to measure the analyzer's output signal.

Note.—Use of a chart recorder in addition to the DM is optional.

(iii) Measure zero air for 60 minutes. During this 60-minute interval, record twenty-five (25) readings at 2-minute intervals. (See Figure B-2 in Appendix A.)

(iv) Convert each DM reading to concentration units (p.p.m.) by reference to the test analyzer's calibration curve as determined in § 53.21(b). Label the converted DM readings r_1, r_2, \dots, r_{25} .

(v) Calculate the standard deviation, S , as follows:

$$S = \sqrt{\frac{\sum_{i=1}^{25} (r_i - \bar{r})^2}{24}} \quad (\text{p.p.m.})$$

where \bar{r} indicates the 4-th DM reading in ppm.

(vi) Let S at 0 ppm be identified as S_0 ; compare S_0 to the noise specification given in Table B-1.

Table B-3, and comparing the test gas-phase reactions that might occur between an interferent and the pollutant caused by the pollutant alone. Known analyzers' response to the response are designated by footnote (3) in Table B-3. In these cases, the interference equivalent of the pollutant.

§ 53.23

Title 40—Protection of Environment

Pollutant	Analyzer type ¹	Hydro- chloric acid	Ammonia gas	Hydro- sulfide gas	Nitro- gen dioxide	Nitro- gen oxide	Carbon dioxide	Ethyl- alcohol	Ozone	Xylene vapor	Water vapor	Carbon monoxide	Methane	Ethane
CO	Gas chromatographic (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical photometric (P.P.D.)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chromatographic	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical-wet	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (potassium iodide reaction)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Spectrophotometric-gas phase	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Flame photometric (F.P.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Gas chromatography (P.D.)	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Chemical (permanganate reaction)	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Electrochemical	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1	0.14	0.1
CO	Conductivity	0.2	0.1	0.1	0.14	0.1	0.14	0.1	0.1					

(C) Test atmosphere Z: Zero air.
(iv) Adjust the individual flow rates and the pollutant or interferent generators for the three test atmospheres as follows:

(A) The flow rates of test atmospheres I and Z shall be identical.

(B) The concentration of pollutant in test atmosphere P shall be adjusted such that when P is mixed (diluted) with either test atmosphere I or Z, the resulting concentration of pollutant shall be as specified in Table B-3.

(C) The concentration of interferent in test atmosphere I shall be adjusted such that when I is mixed (diluted) with test atmosphere P, the resulting concentration of interferent shall be equal to the value specified in Table B-3.

(D) To minimize concentration errors due to flow rate differences between I and Z, it is recommended that, when possible, the flow rate of P be from 10 to 20 times larger than the flow rates of I and Z.

(v) Mix test atmospheres P and Z by passing the total flow of both atmospheres through a mixing flask.

(vi) Sample and measure the mixture of test atmospheres P and Z with the test analyzer. Allow for a stable reading, and record the reading, in concentration units, as R (see Figure B-3).

(vii) Mix test atmospheres P and I by passing the total flow of both atmospheres through a mixing flask.

(viii) Sample and measure this mixture. Record the stable reading, in concentration units, as R_i .

(ix) Calculate the interference equivalent (IE) as:

$$IE = R_i - R$$

IE must be equal to or less than the specification given in Table B-1 for each interferent to pass the test.

(x) Follow steps (iii) through (ix), in turn, to determine the interference equivalent for each interferent.

(xi) For those interferents which cannot be mixed with the pollutant as indicated by footnote (3) in Table B-3, adjust the concentration of test atmosphere I to the specified value without being mixed or diluted by the pollutant test atmosphere. Determine IE as follows:

(A) Sample and measure test atmosphere Z (zero air). Allow for a stable reading and record the reading, in concentration units, as R .

(B) Sample and measure the interferent test atmosphere I. If the test analyzer

is not capable of negative readings, adjust the analyzer (not the recorder) to give an offset zero. Record the stable reading in concentration units as R_i , extrapolating the calibration curve, if necessary, to represent negative readings.

(C) Calculate $IE = R_i - R$. IE must be equal to or less than the specification in Table B-1 to pass the test.

(xii) Sum the absolute value of all the individual interference equivalents. This sum must be equal to or less than the total interferent specification given in Table B-1 to pass the test.

(e) Zero Drift, Span Drift, Lag Time, Rise Time, Fall Time, and Precision—(1) Technical Definitions—(i) Zero Drift: The change in response to zero pollutant concentration, over 12- and 24-hour periods of continuous unadjusted operation.

(ii) Span Drift: The percent change in response to an up-scale pollutant concentration over a 24-hour period of continuous unadjusted operation.

(iii) Lag Time: The time interval between a step change in input concentration and the first observable corresponding change in response.

(iv) Rise Time: The time interval between initial response and 95 percent of final response after a step increase in input concentration.

(v) Fall Time: The time interval between initial response and 95 percent of final response after a step decrease in input concentration.

(vi) Precision: Variation about the mean of repeated measurements of the same pollutant concentration, expressed as one standard deviation about the mean.

(2) Tests for these performance parameters shall be accomplished over a period of seven (7) or more days. During this time, the line voltage supplied to the test analyzer and the ambient temperature surrounding the analyzer shall be varied from day to day. One test result for each performance parameter shall be obtained each test day, for seven (7) or fifteen (15) test days as necessary. The tests are performed sequentially in a single procedure.

(3) The 24-hour test day may begin at any clock hour. The first 12 hours out of each test day are required for testing 12-hour zero drift. Tests for the other parameters shall be conducted during the remaining 12 hours.

(4) Table B-4 specifies the line voltage and room temperature to be used for each test day. The line voltage and temperature shall be changed to the specified values at the start of each test day (i.e., at the start of the 12-hour zero test). Initial adjustments (day zero) shall be made at a line voltage of 115 volts (rms) and a room temperature of 23° C.

(5) The tests shall be conducted in blocks consisting of 3 test days each until 7 or 15 test results have been obtained. (The final block may contain fewer than three test days.) If a test is interrupted by an occurrence other than a malfunction of the test analyzer, only the block during which the interruption occurred shall be repeated.

(6) During each block, manual adjustments to the electronics, gas, or reagent flows or periodic maintenance shall not be permitted. Automatic adjustments which the test analyzer performs by itself are permitted at any time.

(7) At least 4 hours prior to the start of the first test day of each block, the test analyzer may be adjusted and/or serviced according to the periodic maintenance procedures specified in the manual referred to in § 53.4(b)(3). If a new block is to immediately follow a previous block, such adjustments or servicing may be done immediately after completion of the day's tests for the last day of the previous block and at the voltage and temperature specified in Table B-4.

TABLE B-4.—Line voltage and room temperature test conditions

Test day	Line voltage, ¹ rms	Room temperature, ² °C	Comments
0	115	23	Initial set-up and adjustments.
1	115	23	
2	115	23	
3	115	23	Adjustments and/or periodic maintenance permitted at end of test.
4	115	23	
5	115	23	
6	115	23	
7	115	23	Adjustments and/or periodic maintenance permitted at end of test.
8	115	23	
9	115	23	Examine test results to ascertain if further testing is required.
10	115	23	Adjustments and/or periodic maintenance permitted at end of test.
11	115	23	
12	115	23	
13	115	23	Adjustments and/or periodic maintenance permitted at end of test.
14	115	23	
15	115	23	

¹ Voltage specified shall be controlled to ±1 volt.

² Temperature specified shall be controlled to ±1°C.

perature specified for that day, but only on test days 3, 6, 9, and 12.

Note—If necessary, the beginning of the test day, including such maintenance or adjustment may be delayed as necessary to complete the service or adjustment operation.

(8) All response readings to be recorded shall first be converted to concentration units according to the calibration curve. Whenever a stable reading is to be measured, the test atmosphere shall be measured long enough to cause a change in response of at least 10% of full scale. Identify all readings and other pertinent data on the strip chart (See Figure B-1 illustrating the pattern of the required readings.)

(9) Test Procedure. (i) Arrange to generate pollutant test atmospheres as follows:

Test atmosphere:
 A_0 —zero air.
 A_1 —20-25 of the upper range limit.
 A_2 —50-55 of the upper range limit.
 A_3 —80-85 of the upper range limit.
 A_4 —90-95 of the upper range limit.

Test atmospheres A_0 , A_1 , and A_2 shall be consistent during the tests and from day to day.

than the specified value to pass the test for zero drift.

(ii) *Span Drift*
(A) Span drift at 20 percent of URL (MSD):

$$MSD_s = \frac{M_s - M_{s-1}}{M_{s-1}} \times 100\%$$

or

$$MSD_s = \frac{M_s - M'_{s-1}}{M'_{s-1}} \times 100\%$$

if span adjustment was made on the previous day, where

$$M_s = \frac{1}{6} \sum_{i=1}^6 P_i$$

s indicates the n-th test day, and i indicates the i-th reading on the nth day.

(B) Span drift at 80 percent of URL (USD):

$$USD_s = \frac{S_s - S_{s-1}}{S_{s-1}} \times 100\%$$

or

$$USD_s = \frac{S_s - S'_{s-1}}{S'_{s-1}} \times 100\%$$

if span adjustment was made on the previous day, where

$$S_s = \frac{1}{6} \sum_{i=1}^6 P_i$$

s indicates the n-th test day, and i indicates the i-th reading on the n-th test day.

(C) Both USD and MSD must be equal to or less than the respective specifications given in Table B-1 to pass the test for span drift.

(iii) *Lag Time*. Determine, from the strip chart, the elapsed time in minutes between the mark made in step (xxvi) and the first observable (two times the noise level) response. This time must be equal to or less than the time specified in Table B-1 to pass the test for lag time.

(iv) *Rise Time*. Calculate 95 percent of reading P_s and determine from the recorder chart, the elapsed time between the first observable (two times noise level) response and a response equal to 95 percent of the P_s reading. This time must be equal to or less than the rise time specified in Table B-1 to pass the test for rise time.

(v) *Full Time*. Calculate five percent of ($P_s - L_s$) and determine, from the strip chart, the elapsed time in minutes between the first observable decrease in response following reading P_s and a response equal to five percent of ($P_s - L_s$). This time must be equal to or less than

P_s ----- Average of P_1, \dots, P_n for the n-th test day.
 P'_s ----- Adjusted span reading at 80 percent of URL on the n-th test day.
 URL ----- Upper range limit.
 USD ----- Span drift at 80 percent of URL.
 Z ----- Average of L_s and L_n .
 Z_n ----- Average of L_n and L_s on the n-th test day.
 Z'_n ----- Adjusted zero reading on the n-th test day.
 ZD ----- Zero drift.
 12ZD ----- 12-hour zero drift.
 24ZD ----- 24-hour zero drift.

Applicant _____ Date _____

Test No. _____

Analyzer _____ Range _____

READING NUMBER	TUE	8% URL		12% URL	
		Obs	Field	Obs	Field
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
$\sum_{i=1}^6 P_i$					
$\sum_{i=1}^6 P'_i$					
$\sum_{i=1}^6 P_i$					
1					

II k

Figure B-2. Form for noise data.

[illegible]

Figure 8-1. Form for data and calculations for lower detectable limit and interference equivalent.

[illegible]

Figure 2-4. Form for recording data for drift and precision.

Applicant		Range		A - 24 TEST DAY													
Analyzer		Range		1	2	3	4	5	6	7	8	9	10	11	12	13	14
TEST POLLUTANT	15 PM ₁₀	CALCULATION															
	20 PM _{2.5}																
TEST POLLUTANT	25 PM _{2.5}																
	30 PM _{2.5}																
TEST POLLUTANT	35 PM _{2.5}																
	40 PM _{2.5}																
TEST POLLUTANT	45 PM _{2.5}																
	50 PM _{2.5}																
TEST POLLUTANT	55 PM _{2.5}																
	60 PM _{2.5}																
TEST POLLUTANT	65 PM _{2.5}																
	70 PM _{2.5}																
TEST POLLUTANT	75 PM _{2.5}																
	80 PM _{2.5}																
TEST POLLUTANT	85 PM _{2.5}																
	90 PM _{2.5}																
TEST POLLUTANT	95 PM _{2.5}																
	100 PM _{2.5}																
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TEST POLLUTANT	115 PM _{2.5}																
	120 PM _{2.5}																
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	220 PM _{2.5}																
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	690 PM _{2.5}																
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	790 PM _{2.5}																
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TEST POLLUTANT	875 PM _{2.5}																
	880 PM _{2.5}																
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	1110 PM _{2.5}																
TEST POLLUTANT	1115 PM _{2.5}																
	1120 PM _{2.5}																
TEST POLLUTANT	1125 PM _{2.5}																
	1130 PM _{2.5}																
TEST POLLUTANT	1135 PM _{2.5}																
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TEST POLLUTANT	1145 PM _{2.5}																
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TEST POLLUTANT	1245 PM _{2.5}																
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TEST POLLUTANT	1275 PM _{2.5}																
	1280 PM _{2.5}																
TEST POLLUTANT	1285 PM _{2.5}																
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TEST POLLUTANT	1295 PM _{2.5}																
	1300 PM _{2.5}																
TEST POLLUTANT	1305 PM _{2.5}																
	1310 PM _{2.5}																
TEST POLLUTANT	1315 PM _{2.5}																
	1320 PM _{2.5}																
TEST POLLUTANT	1325 PM _{2.5}																
	1330 PM _{2.5}																
TEST POLLUTANT	1335 PM _{2.5}																
	1340 PM _{2.5}																
TEST POLLUTANT	1345 PM _{2.5}																
	1350 PM _{2.5} </																

used, dated, signed by the analyst performing the test, and submitted.

(e) *Sample Manifold.* All test concentration measurements shall be made on air sampled from a common intake and distribution manifold, and in such a way that both the candidate method and the reference method receive homogeneous air samples. Precautions shall be taken in the design and construction of this manifold to minimize the removal of particulates and trace gases, and to insure that identical samples reach the two methods. Schematic drawings, physical illustrations, descriptions, and complete details of this manifold system shall be submitted.

[40 FR 7049, Feb. 18, 1975, as amended at 40 FR 18169, Apr. 25, 1975]

§ 53.31 Test conditions.

(a) *All Methods.* All test measurements made of test samples collected shall be at a room temperature between 20° and 30° C., and at a line voltage between 105 and 125 volts. All methods shall be calibrated as specified in paragraph (c) of this section prior to initiation of the tests.

(b) *Automated Methods.* Set-up and start-up of the test analyzer (and the reference method if automated) shall be in strict accordance with the applicable operation manual(s). If the test analyzer does not have an integral strip chart recorder, connect the analyzer output to a suitable strip chart recorder of the servo, null-balance type. This recorder shall have a chart width of at least 25 centimeters, a response time of not more than 0.25 percent of full scale, and capability of either reading measurements at least 5 percent below zero or offsetting the zero by at least 5 percent.

Note.—Other data acquisition components may be used along with the chart recorder during the conduct of these tests. Use of the chart recorder is intended only to facilitate evaluation of data submitted.

Allow adequate warmup or stabilization time as indicated in the applicable operation manual(s) before beginning the tests.

(c) *Calibration.* The reference method shall be calibrated according to the applicable operation manual. A candidate manual method (or portion thereof) shall be calibrated if such calibration is a part of the method. For a candidate automated method, the test analyzer

shall be calibrated according to the manual referred to in § 53.4(b)(3) and as follows: If the chart recorder does not have below zero capability, adjust either the test analyzer's controls or the chart recorder to obtain a +5 percent offset zero reading on the recorder chart to facilitate observing negative drift. Construct and submit a calibration curve showing a plot of recorder scale readings (ordinate) against pollutant concentrations (abscissa). A plot of test analyzer output units (volts, millivolts, milliamperes, etc.) against pollutant concentrations shall also be shown for candidate methods not including integral chart recorders. All such plots shall consist of at least seven (7) approximately equally spaced, identifiable points, including 0 and 90–5 percent of full scale.

(d) *Range.* (1) Except as provided in paragraph (d)(2) of this section, each method shall be operated in the range specified in Table B-1 of Subpart B of this part.

(2) For a candidate method having more than one selectable range, one range must be that specified in Table B-1 and a test analyzer representative of the method must pass the tests required by this subpart while operated in that range. The tests may be repeated for a broader range (i.e., one extending to higher concentrations) than the one specified in Table B-1, provided that the range does not extend to concentrations more than two times the upper range limit specified in Table B-1 and that the test analyzer has passed the tests required by Subpart B of this part (if applicable) for the broader range. If the tests required by this subpart are conducted or passed only for the range specified in Table B-1, any equivalent method determination with respect to the tests will be limited to that range. If the tests are passed for both the specified range and a broader range (or ranges), any such determination will include the broader range(s) as well as the specified range. Appropriate test data shall be submitted for each range sought to be included in such a determination.

(e) *Operation of Automated Methods.* (1) Once the test analyzer has been set up and calibrated and tests started, manual adjustment or normal periodic maintenance is permitted only every 3 days. Automatic adjustments which the test analyzer performs by itself are permitted at any time. At 3-day intervals, only adjustments and periodic maintenance

nance as specified in the manual referred to in § 53.4(b)(3) are permitted. The submitted records shall show clearly when manual adjustments were made and describe the operations performed.

(2) All test measurements shall be made with the same test analyzer; use of multiple test analyzers is not permitted. The test analyzer shall be operated continuously during the entire series of test measurements.

(3) If a test analyzer should malfunction during any of these tests, the entire set of measurements shall be repeated, and a detailed explanation of the malfunction, remedial action taken, and whether recalibration was necessary (along with all pertinent records and charts) shall be submitted.

[40 FR 7049, Feb. 18, 1975, as amended at 40 FR 18169, Apr. 25, 1975]

§ 53.32 Test procedures.

(a) Conduct the first set of simultaneous measurements with the candidate and reference methods:

(1) Table C-1 specifies the type (1- or 24-hour) and number of measurements to be made in each of the three test concentration ranges.

(2) The pollutant concentration must fall within the specified range as measured by the reference method.

(3) The measurements shall be made in the sequence specified in Table C-2, except for the 1-hour SO₂ measurements, which are all in the high range.

(b) For each pair of measurements, determine the difference (discrepancy) between the candidate method measurement and reference method measurement. A discrepancy which exceeds the discrepancy specified in Table C-1 constitutes a failure. (See Figure C-1 in Appendix A for a suggested format for reporting the test results).

(c) The results of the first set of measurements shall be interpreted as follows:

(1) Zero (0) failures: The candidate method passes the test for consistent relationship.

(2) Three (3) or more failures: The candidate method fails the test for consistent relationship.

(3) One (1) or two (2) failures: Conduct a second set of simultaneous measurements as specified in Table C-1. The results of the combined total of first-set and second-set measurements shall be interpreted as follows:

(i) One (1) or two (2) failures: The candidate method passes the test for consistent relationship.

(ii) Three (3) or more failures: The candidate method fails the test for consistent relationship.

(4) For sulfur dioxide, the 1-hour and 24-hour measurements shall be interpreted separately, and the candidate method must pass the tests for both 1- and 24-hour measurements to pass the test for consistent relationship.

(d) A 1-hour measurement consists of the integral of the instantaneous concentration over a 60-minute continuous period divided by the time period. Integration of the instantaneous concentration may be performed by any appropriate means such as chemical, electronic, mechanical, visual judgment, or by calculating the mean of not less than 12 equally spaced instantaneous readings.

Appropriate allowances or corrections shall be made in cases where significant errors could occur due to characteristic lag time or rise/fall-time differences between the candidate and reference methods. Details of the means of integration and any corrections shall be submitted.

(e) A 24-hour measurement consists of the integral of the instantaneous concentration over a 24-hour continuous period divided by the time period. This integration may be performed by any appropriate means such as chemical, electronic, mechanical, or by calculating the mean of twenty-four (24) sequential 1-hour measurements.

(f) For oxidant and carbon monoxide, no more than six (6) 1-hour measurements shall be made per day. For sulfur dioxide, no more than four (4) 1-hour measurements or one (1) 24-hour measurement shall be made per day. One-hour measurements may be made concurrently with 24-hour measurements if appropriate.

(g) For applicable methods, control or calibration checks may be performed once per day without adjusting the test analyzer or method. These checks may be used as a basis for a linear interpolation-type correction to be applied to the measurements to correct for drift. If such a correction is used, it shall be applied to all measurements made with the method, and the correction procedure shall become a part of the method.

App. A Title 40—Protection of Environment
 APPENDIX A—OPTIONAL FORM FOR REPORTING TEST RESULTS

Candidate Method
 Reference Method
 Applicant
☐ First Set ☐ Second Set ☐ Type ☐ 1 hour ☐ 24 hour

CONCENTRATION RANGE	DATE	TIME	CONCENTRATION, PPM		DIFFER- ENCE	TABLE C-1 SPEC.	TABLE C-1 SPEC.
			CANDIDATE	REFERENCE			
LOW	1						
	2						
	3						
	4						
	5						
	6						
MEDIUM	1						
	2						
	3						
	4						
	5						
	6						
HIGH	1						
	2						
	3						
	4						
	5						
	6						
TOTAL VALUES:							

II O

Figure C-1. Form for Subpart C test results.
 [40 FR 7049, Feb. 18, 1975, as amended at 40 FR 18199, Apr. 25, 1975]

Chapter I—Environmental Protection Agency § 53.32
 TABLE C-1. TEST CONCENTRATION RANGE, NUMBER OF MEASUREMENTS REQUIRED, AND MAXIMUM DISCREPANCY SPECIFICATION

Pollutant	Concentration range P/M	Simultaneous measurements required				Maximum discrepancy P/M
		1 hr	First set	Second set	24 hr	
Oxidants	Low 0.04-0.10	5	5	5	5	0.02
	Medium 0.15-0.25	5	5	5	5	0.02
	High 0.35-0.45	5	5	5	5	0.04
Carbon monoxide	Total	14	14	14	14	2.0
	Low 7-11	5	5	5	5	2.0
	High 15-45	4	4	4	4	2.0
Sulfur dioxide	Total	14	14	14	14	0.02
	Low 0.05-0.15	7	7	7	7	0.02
	High 0.20-0.50	7	7	7	7	0.04
Total		7	7	7	7	

TABLE C-2. SEQUENCE OF TEST MEASUREMENTS

Measurement	Concentration range	
	First set	Second set
1	Low	Medium
2	High	High
3	Low	High
4	High	High
5	Low	Medium
6	Medium	Low
7	Medium	Medium
8	High	Low
9	High	High
10	Medium	Low
11	High	Medium
12	Low	High
13	Medium	Medium
14	High	High
15	Low	Medium
16	Medium	Low
17	High	High
18	Low	High

APPENDIX III

GUIDELINE FOR PUBLIC REPORTING OF DAILY AIR QUALITY

ENVIRONMENTAL PROTECTION AGENCY

[FRL 610-6]

GUIDELINE FOR PUBLIC REPORTING OF DAILY AIR QUALITY

Pollutant Standards Index (PSI)
(OAQPS Number 1.2-044)

PREPARED BY

EPA WORKING GROUP TO DEVELOP AN AIR
QUALITY INDEX

CONTRIBUTING AGENCIES; U.S. ENVIRON-
MENTAL PROTECTION AGENCY, OFFICE OF
RESEARCH AND DEVELOPMENT, OFFICE OF
AIR AND WASTE MANAGEMENT, OFFICE OF
PLANNING AND MANAGEMENT

NATIONAL OCEANIC AND ATMOSPHERIC
ADMINISTRATION—AUGUST, 1976

The U.S. Environmental Protection
Agency's recommended "Pollutant
Standards Index" (PSI) is the result of
a joint effort on the part of EPA's Offices
of Research and Development, Air and

Waste Management, and Planning and
Management. The guideline was pre-
pared by the EPA Working Group to
Develop an Air Quality Index in response
to a request from the Federal Inter-
agency Task Force on Air Quality Indi-
cators of which EPA is a member. The
Federal Task Force, chaired by the
Council on Environmental Quality, was
created as a result of a joint EPA/CEQ
report¹ which pointed out existing prob-
lems resulting from the present diversity
of indices used in the United States and
Canada.

This guideline suggests the use of the
Pollutant Standards Index (PSI) for
those local and state air pollution con-
trol agencies wishing to report an air
quality index on a daily basis. The PSI
places maximum emphasis on protecting
the public health; that is, it advises the
public of any possible adverse health ef-
fects due to pollution. In order to err
on the side of public safety, the index
stresses reporting on the basis of the
stations with the highest pollutant con-
centrations and assumes that other un-
sampled portions of the community will
also experience high concentrations. In
addition, its emphasis is upon acute
health effects occurring over very short
time periods (24 hours or less) rather
than chronic effects occurring over
months or years. It is not intended for,
and should not be used for, ranking ur-
ban areas in terms of the severity of their
air pollution problems. Such rankings
require the use of many other kinds of
environmental data not incorporated in
this index.

Finally, Appendix A discusses the
meteorological information needs of
forecasting relative index changes. This
was prepared by personnel from the Na-
tional Oceanic and Atmospheric Ad-
ministration.

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1. EXECUTIVE SUMMARY

This guideline suggests the use of the
Pollutant Standards Index (PSI) for
those local and state air pollution control
agencies wishing to report an air quality
index on a daily basis. The document also
includes appropriate monitoring and re-

porting guidance. The guideline is the
result of an earlier study¹ showing that
of all the air quality indices in use today,
no two are exactly the same. A potentially
serious problem of public confusion can
occur in regions where neighboring states
and cities use different indices. The PSI

See footnotes, p. 37669.

also responds to the request of several state and local agencies that the U.S. Environmental Protection Agency provide them with a recommended uniform air quality index.

The recommended index incorporates five pollutants—carbon monoxide, sulfur dioxide, total suspended particulate, photochemical oxidants, and nitrogen dioxide—for which there are short-term (24 hours or less) health-related National Ambient Air Quality Standards (NAAQS),¹ and/or Federal Episode Criteria,^{2,3} and Significant Harm Levels.^{4,5} A sixth variable—the product of total suspended particulate and sulfur dioxide—is computed and is included in the index equation. This variable and also nitrogen dioxide are treated differently than the other pollutants because they have no short-term NAAQS. Therefore, they are reported when they exceed the Federal Episode Criteria and Significant Harm Levels. Because of the basic design of the index, any further pollutant requiring NAAQS, Federal Episode Criteria, and Significant Harm Levels can be readily added.

The index uses a "segmented linear function"⁶ to convert each air pollutant concentration into a normalized number. The NAAQS for each pollutant corresponds to $PSI=100$, and the Significant Harm Level corresponds to $PSI=500$.

At a minimum, PSI reports that pollutant with the highest index value of all the pollutants being monitored, a dimensionless number, and a descriptor word. On days when two or more pollutants violate their respective NAAQS, each of the pollutants should be reported. Five descriptor words have been chosen to characterize daily air quality: "good," "moderate," "unhealthful," "very unhealthful," and "hazardous." In addition, for each descriptor word, generalized health effects and cautionary statements are provided for use when the air is characterized as "unhealthful" or worse.

For large metropolitan areas comprised of many smaller cities and suburbs where significant air quality differences may exist, the air pollution control agency may wish to report separate index values for each community. This has the advantage of showing the public how air pollution varies over the larger metropolitan area. The pollutants would be monitored at population-oriented locations where the maximum concentration for the particular pollutant is expected to occur, and the public within each community would be made aware of the worst air quality to which it is exposed.

Further guidance is given on the measurements practices and monitor siting considerations (Section 5).

PSI should not be used to rank cities. An evaluation of PSI in eight cities⁷ illustrated the difficulties of attempting to compare air quality levels in different cities using this or any other index. PSI

is designed for the daily reporting of air quality to advise the public of potentially acute, but not chronic health effects. To properly rank the air pollution problems in different cities, one should rely not just on air quality data, but should include all data on population characteristics, daily population mobility, transportation patterns, industrial composition, emission inventories, meteorological factors, and the spatial representativeness of air monitoring sites. A correct ranking should also consider the number of people actually exposed to various concentrations, as well as the frequency and duration of their exposure.

Adoption of PSI should reduce the confusion due to the existence of many indices. PSI has several advantages: (1) it is simple and can be easily understood by the public, (2) it can accommodate new pollutants, (3) it is based on a reasonable scientific premise, (4) it relates to NAAQS, Federal Episode Criteria, and Significant Harm Levels, (5) it exhibits day-to-day variations, and (6) a qualitative trend in the index can be forecast for periods up to a day in advance, especially during episodic conditions.

2. INTRODUCTION

A major area of concern in the field of air pollution control is how to best report daily air quality to the public. A recent CEQ/EPA Report⁸ indicates that of the 55 largest U.S. metropolitan air pollution control agencies, 33 use an air pollution index. In addition, five states and two Canadian Provinces operate state-wide (or Province-wide) index systems. With two minor exceptions, no two indices were found to be exactly the same. The public confusion generated by the use of so many indices is particularly evident in bordering states using different indices. Therefore, there is a need to develop a uniform index to report the daily status of air pollution.

A recent paper⁹ emphasizes the need for a truly meaningful index to have a sound scientific basis. The paper suggests that such an index be based on the relationship between pollutant concentration and adverse health (welfare) effects—that is, a "damage function." Unfortunately, it is an extremely complex undertaking to relate measured air pollutant concentrations to the many diverse effects of air pollution—for example, aggravation of disease in susceptible people, increased incidence of respiratory illness in healthy persons, impairment of human motor function, reduced visibility, corrosion of materials, and soiling of buildings. Arriving at an air quality standard for a given pollutant—which is just one point in a damage function—has required vast quantities of data, medical advisory committees, detailed epidemiological studies, and other extensive research. The air quality criteria documents published for the major air pollutants¹⁰⁻¹⁴ reflect the complexity of the process.

The recent paper⁹ also emphasizes the importance of an index accounting for the adverse effects associated with com-

binations of pollutants—that is, synergism. For example, the criteria document on sulfur oxides¹² states that adverse health effects attributable to sulfur oxides are intensified in the presence of particulate matter. Understanding synergistic effects adds greatly to the problem of obtaining a truly meaningful air quality index. These problems stress the need for additional research to develop pollutant-related damage functions—that take into account synergistic effects on health and welfare.

As an interim solution to these problems, this guideline recommends a uniform index to report daily air quality, along with appropriate monitoring guidance. This index will serve until a more meaningful air quality index can be created. If adopted, a uniform index should end the confusion associated with the use of many varied indices.

3. THE EPA RECOMMENDED DAILY INDICATOR—POLLUTANT STANDARDS INDEX (PSI)

The Pollutant Standards Index (PSI or ψ) is the result of a joint effort by EPA's Offices of: Research and Development, Air and Waste Management, and Planning and Management. Its evolution has included formulation of several candidate index structures,¹⁵ and the index has undergone an extensive review process involving state and local air pollution control agencies, public organizations, and media representatives.

The recent CEQ/EPA compendium of air pollution indices⁸ developed an "index classification system" to analyze and compare the various indices used by state, Provincial, and local agencies. Indices were categorized according to four criteria: (1) number of pollutant variables measured, (2) calculation method used to compute the index, (3) descriptor categories reported with the index, (4) method of reporting (whether it is "combined," "maximum," or "individual").

The report found that the greatest number of the indices in use⁸ incorporate five of the six National Ambient Air Quality Standards (NAAQS) pollutants (hydrocarbons are excluded because there are no direct health effects associated with the pollutant. It is controlled because it is a precursor to the formation of photochemical oxidants.); (2) use a segmented linear function⁶; (3) are based on the maximum of one of the pollutant variables; and (4) use three to five descriptor categories.

In the following sections, the structure of PSI is presented according to the "index classification system" categories.

3.1 Number of pollutants

PSI includes five pollutants: carbon monoxide (CO), sulfur dioxide (SO₂), total suspended particulate matter (TSP), photochemical oxidant (O₃) and nitrogen dioxide (NO₂). Primary (that is,

⁶ A segmented linear function consists of two or more straight lines, drawn between successive coordinates ("breakpoints") where each line may have a different slope.

See footnotes, p. 37669.

⁶ A segmented linear function consists of two or more straight lines, drawn between successive coordinates ("breakpoints") where each line may have a different slope.

health related) NAAQS, and/or Federal Episode Criteria, and Significant Harm Levels exist for all five. In addition, one pollutant product TSP \times SO₂ is included because it has both Federal Episode Criteria and a Significant Harm Level.^a As with NO_x, which has no short-term primary NAAQS, the product is reported when the Federal Episode or Significant Harm Levels are exceeded. Finally, because of the structure of the index, any pollutant identified in the future for which NAAQS, Federal Episode Criteria, and Significant Harm Levels are adopted can be added without modifying the basic form of the index.

3.2 Calculation method

A segmented linear function is used relating actual air pollution concentrations to a normalized number. For example, PSI (ψ) equals 100 when the NAAQS for each pollutant is reached, while (ψ) equals 500 when the Significant Harm Level for each pollutant is reached. The normalized number should be easier for the general public to understand because it does not require one to know specific NAAQS concentrations or the many different Federal Episode and Significant Harm Levels.

The index breakpoints are listed in metric units (Table 1) and in parts per million (Table 2). The first breakpoint separates the descriptor categories "good" and "moderate." For CO and O₃, the first breakpoint was chosen at 50 percent of the primary NAAQSs. In the case of TSP and SO₂, concentrations equal to their respective primary annual NAAQS were chosen because the frequent occurrence of values greater than these concentrations could lead to violations of their respective annual NAAQS. In an area where a violation of either the annual primary TSP or SO₂ standard occurs, approximately 50 percent or more of the days will thus be classified as "moderate" or worse. This approach minimizes the potential for public confusion which might arise from a preponderance of days reported as "good," followed by the report that the annual health-related standards has been violated.

The breakpoints between the primary NAAQS and Significant Harm Levels are somewhat arbitrarily set at the Federal Episode Alert, Warning, and Emergency Levels, except for oxidants. In the case of oxidant, 400 $\mu\text{g}/\text{m}^3$ was used as the PSI breakpoint for the descriptor words "unhealthy" and "very unhealthy" because it appears to be more consistent with the descriptor words than the suggested administrative Alert level of 200 $\mu\text{g}/\text{m}^3$.^{**}

^{**} Several air pollution control agencies are using 400 $\mu\text{g}/\text{m}^3$ instead of 200 $\mu\text{g}/\text{m}^3$ as their Alert level with concurrence by the Environmental Protection Agency.

See footnotes, p. 37669.

TABLE 1. Breakpoints for PSI (ψ) in Metric Units

Breakpoints	PSI Value (ψ)	TSP $\mu\text{g}/\text{m}^3$ 24-hr.	SO ₂ $\mu\text{g}/\text{m}^3$ 24-hr.	TSP \times SO ₂ ($\mu\text{g}/\text{m}^3$) ²	CO $\mu\text{g}/\text{m}^3$ 8 hours	O ₃ $\mu\text{g}/\text{m}^3$ 1-hr.	NO ₂ $\mu\text{g}/\text{m}^3$ 1-hr.
50% of primary short-term NAAQS	50	75 ^a	80 ^a	b	5.0	80	b
Primary short-term NAAQS	100	260	365	b	10.0	160	b
Alert Level	200	375	800	65 \times 10 ³	17.0	400 ^c	1130
Warning Level	300	625	1600	261 \times 10 ³	34.0	800	2260
Emergency Level	400	875	2100	393 \times 10 ³	46.0	1000	3000
Significant Harm Level	500	1000	2620	490 \times 10 ³	57.5	1200	3750

^a Annual primary NAAQS.

^b No index value reported at concentration levels below those specified by the Alert level criteria.

^c For the PSI index 400 $\mu\text{g}/\text{m}^3$ appears to be a more consistent breakpoint between the descriptor words "unhealthy" and "very unhealthy" than the O₃ Alert Level of 200 $\mu\text{g}/\text{m}^3$.

TABLE 2. Breakpoints for PSI (ψ) in Parts Per Million

Breakpoints	PSI Value (ψ)	SO ₂ 24-hr.	TSP \times SO ₂ ($\mu\text{g}/\text{m}^3$) ² ppm	CO 8 hours	O ₃ 1-hr.	NO ₂ 1-hr.
50% of primary NAAQS	50	.03 ^a	b	2.5	0.04	b
Primary NAAQS	100	.14	b	9.0	0.08	b
Alert Level	200	.30	22.727	15.0	0.20 ^c	0.60
Warning Level	300	.60	91.259	30.0	0.40	1.20
Emergency Level	400	.80	137.413	40.0	0.50	1.60
Significant Harm Level	500	1.00	171.329	50.0	0.60	2.00

^a Annual primary NAAQS.

^b No index value reported at concentration levels below those specified by the Alert Level criteria.

^c For the PSI index 0.2 ppm appears to be a more consistent breakpoint between the descriptor words "unhealthy" and "very unhealthy" than the O₃ Alert Level of 0.1 ppm.

Figures 1 through 5 show the segmented linear function for each of the NAAQS pollutants, and Figure 6 shows the function for the product of TSP and SO₂. If NAAQS for new pollutants are adopted in the future, they can be accommodated by drawing a new segmented linear function.

3.3 Descriptor categories

PSI is primarily a health related index as shown by the descriptor words: "good," "moderate," "unhealthy," "very unhealthy," and "hazardous," (Table 3).

The breakpoints used to separate these descriptor words are somewhat arbitrary. On the basis of health effects data above, it is not possible to establish a sharp demarcation between any two descriptor words. However, when the five pollutants were examined in the context of severity of health effects, their NAAQS and EPA suggested administrative Alert, Warning, and Emergency levels tended to provide convenient breakpoints, except for the oxidant Alert level, which was replaced with 400 $\mu\text{g}/\text{m}^3$, as discussed earlier.

TABLE 2. COMPARISON OF PSI VALUES WITH POLLUTANT CONCENTRATIONS, DESCRIPTOR WORDS
GENERALIZED HEALTH EFFECTS, AND CAUTIONARY STATEMENTS

INDEX VALUE	AIR QUALITY LEVEL	POLLUTANT LEVELS					HEALTH EFFECT DESCRIPTOR	GENERAL HEALTH EFFECTS	CAUTIONARY STATEMENTS
		SO ₂ (24-hour), ppm/m ³	CO (8-hour), ppm/m ³	O ₃ (1-hour), ppm/m ³	NO ₂ (1-hour), ppm/m ³				
500	SIGNIFICANT HARM	1000	87.5	1200	2750				
400	EMERGENCY	875	48.8	1000	2000		HAZARDOUS	Promotes death of ill and elderly. Healthy people will experience severe symptoms that affect their normal activity.	All persons should remain indoors, keep windows and doors closed, and avoid strenuous physical activity.
300	WARNING	625	34.9	800	2250			Promotes onset of certain diseases in addition to significant aggravation of symptoms and decreased exercise tolerance in healthy persons.	Elderly and persons with existing diseases should stay indoors and avoid physical exertion. General population should avoid outdoor activity.
200	ALERT	375	17.9	400 ^a	1130		VERY UNHEALTHFUL	Significant aggravation of symptoms and decreased exercise tolerance in persons with heart or lung disease, with widespread symptoms in the healthy population.	Elderly and persons with existing heart or lung disease should stay indoors and avoid physical activity.
100	HAZAROUS	200	10.9	160	8		UNHEALTHFUL	Mild aggravation of symptoms in susceptible persons, with irritating symptoms in the healthy population.	Persons with existing heart or respiratory ailments should reduce physical exertion and outdoor activity.
00	60% OF HAZAROUS	75 ^b	8.9	80	8		MODERATE		
0		0	0	0	0		GOOD		

^aThe index value reported at concentration level below those specified by "Alert Level" criteria.

^bAssumed primary HAAQS.

4400 ppb/m³ was used instead of the O₃ Alert Level of 200 ppb/m³ (see text).

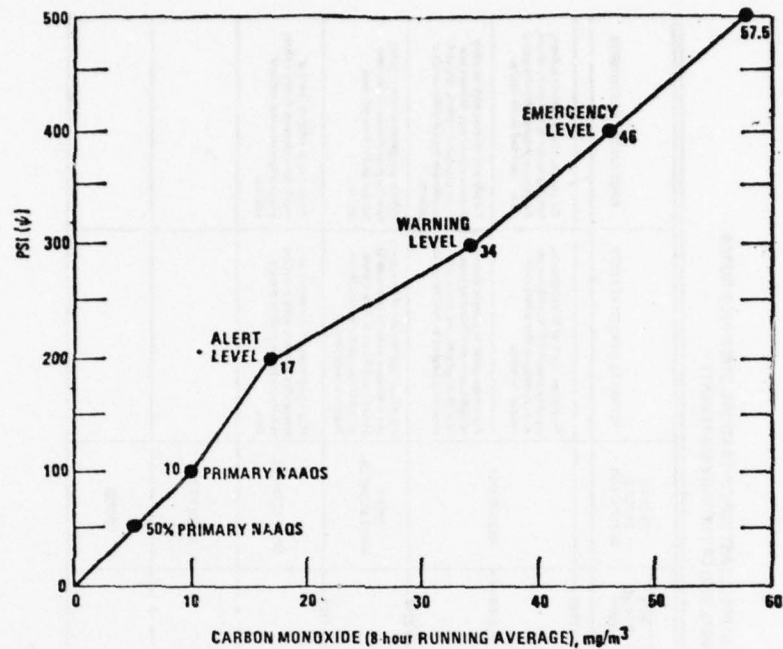


Figure 1. PSI function for carbon monoxide

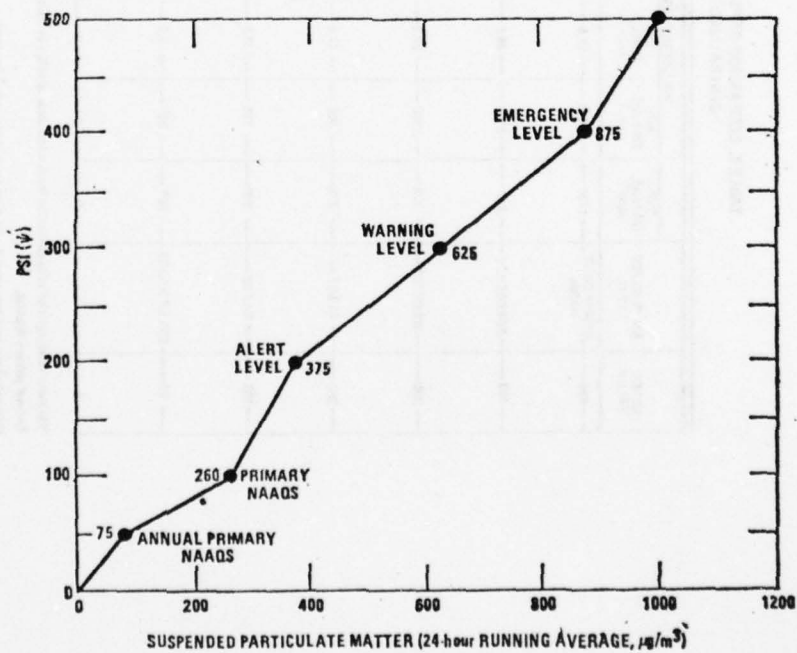


Figure 2. PSI function for suspended particulate matter

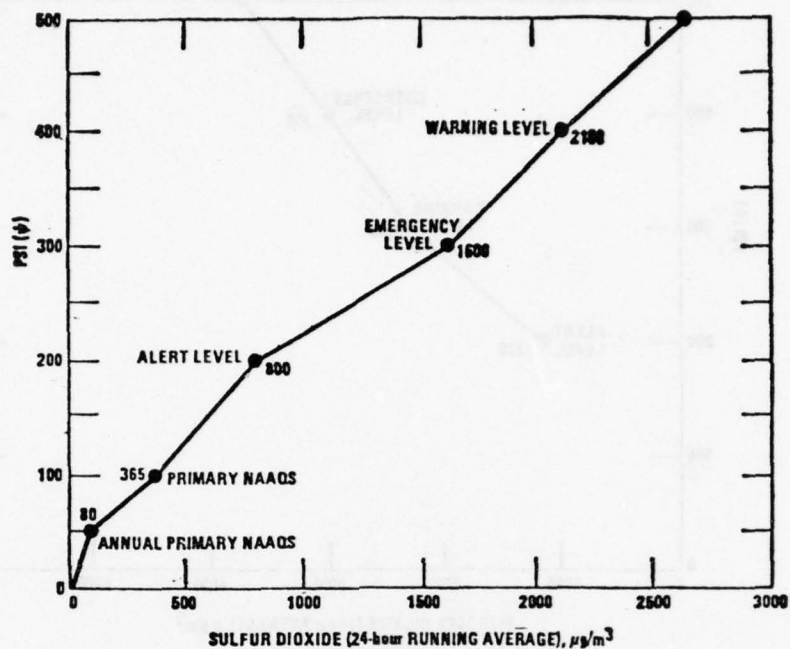


Figure 3. PSI function for sulfur dioxide

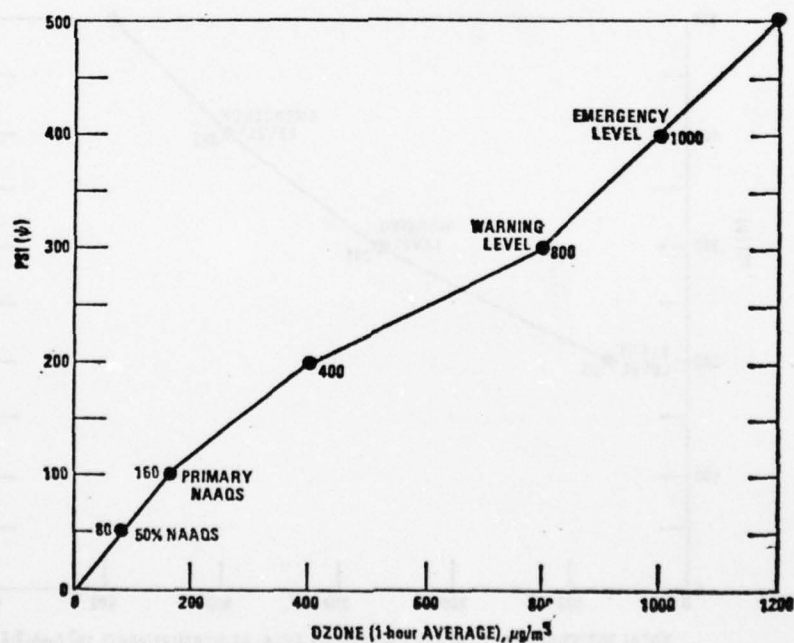


Figure 4. PSI function for photochemical ozone

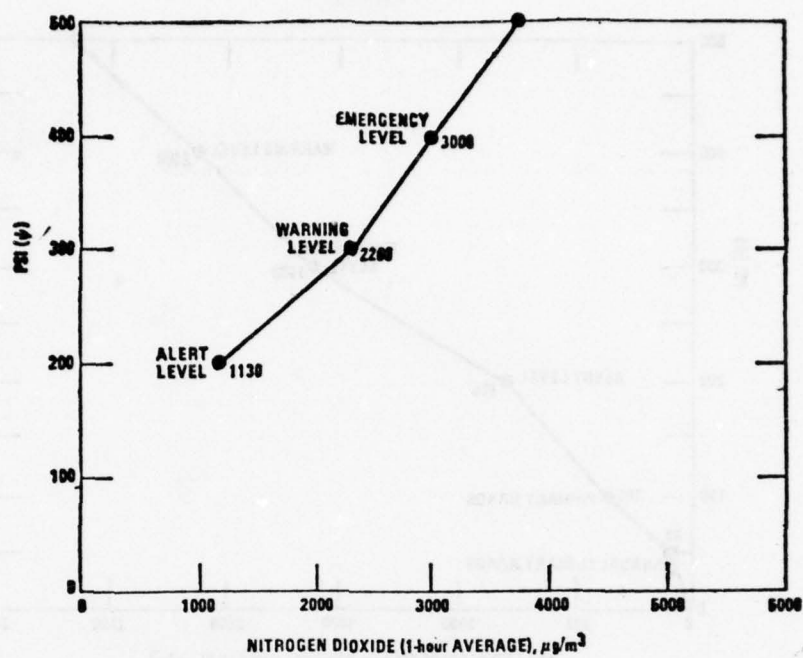


Figure 5. PSI function for nitrogen dioxide.

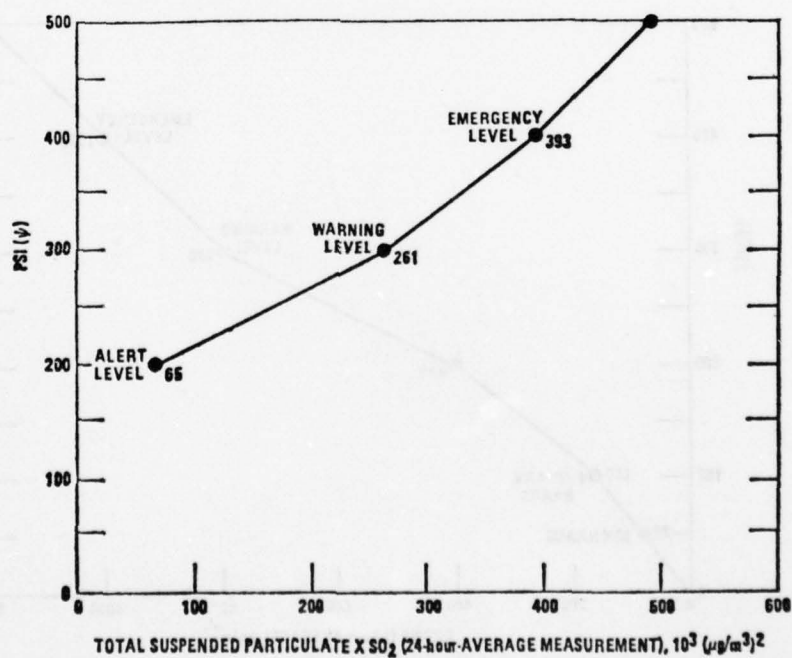


Figure 6. PSI function for product of total suspended particulate and sulfur dioxide

Air pollution levels between the short-term primary NAAQS and the Alert level for TSP, SO_2 , and CO and $400 \mu\text{g}/\text{m}^3$ for O_3 are deemed "unhealthful," because mild aggravation of respiratory symptoms in susceptible persons and irritation symptoms in the healthy population occur at some point above the short-term primary NAAQS and at and below the Alert levels for TSP, SO_2 , and CO and $400 \mu\text{g}/\text{m}^3$ for O_3 . NO_2 is not reported until concentrations exceed the Alert level because no short-term NAAQS has been established. Air pollution concentrations above the Alert level but below the Warning level are classified as "very unhealthful," while concentrations above the Warning level are "hazardous."

These classifications are related to generalized health effects and appropriate cautionary statements (Table 3). A single set of generalized health effects and cautionary statements is indicated for the descriptor words "unhealthful" and "very unhealthful." The "hazardous" category has two sets of generalized health effects and cautionary statements. The first set is reported when the index exceeds 300 and the second when the index exceeds 400 indicating the increasing severity of the air pollution levels.

In the case of TSP and SO_2 , short-term secondary air quality standards also exist below their primary NAAQS. Secondary standards are designed to protect against the adverse effects of pollution on the public welfare (animals, vegetation, materials, visibility, etc.) According to PSI, if their short term secondary NAAQS are violated, the concentrations would be classified as "moderate" or worse. While this descriptor word is valid from a health viewpoint, the air quality is unsatisfactory from the standpoint of welfare effects. Because PSI is a health-related index, the user may wish to report on the possible welfare effects when either the short term TSP or SO_2 NAAQS is violated.

4. REPORTING PROCEDURES

PSI has been designed to be as flexible as possible in allowing air pollution control agencies to decide for themselves the information to include in their reports to the various media. This section examines the recommended method of reporting the index, the reporting of the Federal Episode Criteria, and the concept of flexible media reporting.

4.1 Reporting the index

Since each pollutant is examined separately by comparing its measured concentration with the NAAQS, the Episode Levels, and the Significant Harm Level, each pollutant can be reported separately. At the minimum, the pollutant with the highest index value should be reported to advise the public of the worst air pollution to which it is exposed. On days when two or more pollutants violate their respective NAAQS—that is, have PSI values greater than 100—then each of the pollutants should be reported. The index values of the other pollutants may also be reported for completeness. When the air pollution level is reported as "un-

healthful," "very unhealthful," or "hazardous," cautionary statements should also be used. In addition, the generalized health effects can be used.

Users of PSI may wish to report on the health effects of each pollutant individually, thereby providing more detailed language on each pollutant than is available in Table 3. In preparing such information for the public, the user is encouraged to seek appropriate medical advice and to consult the literature.²⁰⁻²⁴

4.2 Reporting the Federal episode criteria

When the Federal Episode Levels for each pollutant are exceeded, the user should report the administrative actions associated with the Alert, Warning, or Emergency Levels. The issuance of administrative actions depends, of course, upon the forecast of meteorological conditions affecting future pollution levels.

Issuance of administrative actions also apply to the product of TSP and SO_2 , which has both Federal Episode Criteria and Significant Harm Levels.²⁵ Although available health effects information has not been codified to tie the descriptor words to the product of TSP and SO_2 , the product is included for purposes of administrative completeness.

4.3 Forecasting the index

The forecasting of a quantitative index for periods up to a day in advance would be difficult without extensive meteorological data and specialized expertise that some air pollution control agencies may not possess. However, qualitative index forecasting is practicable using the National Weather Service's Air Pollution Weather Forecast Program.²⁶ With this weather information, along with available emissions and air quality trend data, agencies can develop techniques or procedures to forecast the relative change in the index by using the following word descriptors: No significant change, decrease, or increase. The principal responsibility for obtaining the necessary emission and air quality information lies with the air pollution control agency using the index. The air pollution control agency would integrate the meteorological information and apply the predictive methods to generate the forecast. The information needs for forecasting relative index changes is discussed further in Appendix A.

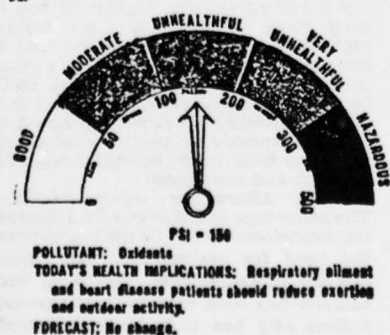
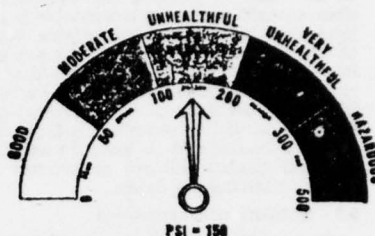


Figure 7. Diagram of possible PSI report for oxidants.



POLLUTANT: Oxidants
TODAY'S HEALTH IMPLICATIONS: Respiratory ailments and heart disease patients should reduce exertion and outdoor activity.
FORECAST: No change.

Figure 8. Diagram of possible PSI report for oxidants.

4.4 Flexible media reporting

The index has been designed to be as flexible as possible in reporting the status of air quality to the public. Either short or long reports can be used. For television, the report could read, "Today the air pollution index is 50, the air quality is good." However, when the air pollution becomes unhealthful, then several possible reports could be considered for television, the news media, or telephone recordings. For example, when oxidant pollution reaches a concentration of $280 \mu\text{g}/\text{m}^3$ (0.14 ppm), the report could take several different forms.

(1) Today, the air pollution index is 150. The air is "unhealthful." The pollutant O_3 is responsible.

(2) An air pollution alert has (or has not) been called based on the forecast for the remainder of the day (and/or) tomorrow.

(3) Repeat the above and add the following cautionary statements: "Persons with existing heart or respiratory ailments should reduce physical exertion and outdoor activity."

(4) The report could include everything said in (1), (2), and (3) and then add that "unhealthful" air can cause "mild aggravation of symptoms in susceptible persons, with irritation symptoms in the healthy population."

(5) Finally, the report could conclude with the forecast of tomorrow's air pollution level, such as "no change in the air pollution level is expected."

Table 3 should be referred to in preparing the air pollution status report to the public. Figures 7 and 8 illustrate the above ozone example by showing possible reports for the television and newspaper, respectively. Both figures provide essential information, indicating the PSI value, the critical pollutant, the health implications for the public, and the next day's forecast. Each of the descriptor categories has been given equal weight. The information is displayed so that it can be presented as rapidly as possible in an easy-to-understand format.

5. MONITORING REQUIREMENTS

5.1 Need for monitoring uniformity

In order for PSI to be readily accepted, the data used in calculating the index must be comparable from site to site within a region. Since these data are to

be obtained at existing air monitoring sites, certain easily implementable practices can eliminate considerable variability in the data. Among these are using: (1) uniformity of site types—that is, residential, commercial, etc.; (2) Federal Reference Methods or their equivalent; (3) standardizing sampling height and probe exposure; and (4) good housekeeping and quality control procedures to provide high quality data.

5.2 Network considerations

Air pollution control agencies need not undertake additional monitoring requirements in the implementation of PSI, but can simply select sites from their existing network. The sites selected, however, should generally meet two basic criteria: (1) Sites should be representative of population exposure—that is, not unduly influenced by a single emission point or background-oriented, and (2) sites should be located in areas of maximum concentration for the pollutant of interest, but should not be unduly influenced by any single source. Areas suitable for monitoring, by pollutant are:

TSP—populated areas substantially downwind of large sources or in the midst of numerous area sources.

SO₂—populated areas substantially downwind of large sources or in the midst of numerous area sources.

CO—densely populated, high-traffic volume areas, including areas in the center city.

O₃—populated areas substantially downwind of areas of maximum hydrocarbon emissions density, such as the central business district. The site should be 100 meters or more removed from major traffic arteries or parking lots.

NO_x—populated areas downwind of areas of high traffic density.

If a pollutant(s) is (are) measured at several locations within a metropolitan area, it would be desirable (if possible) to base the index on the site showing the highest reading on a given day. This would mean that different sites would be used on different days.

For large metropolitan areas comprised of many smaller cities and suburbs where significant air quality differences may exist, the air pollution control agency may wish to report separate index values for each community. This has the additional advantages of showing the public how air pollution varies over the larger metropolitan area. Furthermore, for example, the photochemical pollutants tend to be higher in the suburban fringe.

5.3 Measurement practices and reporting frequencies

5.3.1 Use of Federal reference methods. Since PSI is based on the NAAQS, the Federal Reference Methods (FRM) or equivalent should be used where possible. Such methods are consistent with the averaging time of the primary standards. Further, continuous methods should be used, where possible, to facilitate the reporting of the index numbers two or three times per day.

5.3.2 Carbon monoxide, nitrogen dioxide, and ozone. The FRM for CO is based on the nondispersive infrared

measurement principle. The proposed method for NO_x and the existing method for O₃ employ the chemiluminescence measurement principle and give continuous data. A FRM or equivalent method for CO, NO_x, and O₃ must also meet performance specifications set forth in the Federal Register.

5.3.3 Sulfur dioxide. The FRM for SO₂ is the pararosaniline 24-hour bubbler method. The solution may be analyzed automatically or manually at the central laboratory. Serious logistics problems can arise if an index number must be calculated from multiple sites two or three times per day. Fortunately, there are procedures for designating continuous SO₂ analyzers as equivalent to the FRM, and from these 24-hour running averages are easily obtained. Therefore, the use of the continuous SO₂ analyzer is recommended to collect the data used in the index. If one is not available, then a pararosaniline 24-hour bubbler method can be used if several precautions are taken. To prevent deterioration in the sample, the sample should be collected at ambient temperature or no warmer than 15° C if ambient temperatures are below freezing. The sample should then be analyzed as soon as possible, with no later than a six-hour delay from end of sampling to analysis.

5.3.4 Total suspended particulate. The FRM for TSP uses a high-volume sampler and specifies a midnight-to-midnight 24-hour sample followed by a 24-hour equilibration at a relative humidity less than 50 percent. This leads to a two-day delay in the reported value. For index reporting, the simplest modification to the FRM is to make the sampling time more convenient—that is, 8 a.m.-to-8 a.m. or noon-to-noon, etc. The sample could be weighed immediately to provide a TSP value for the index. Later a true value could be calculated after the recommended equilibration time of 24 hours. A study in EPA Region IV has shown that the true TSP values are usually within 10 percent of the values measured immediately after collection. The true value would be recorded as the correct one, reported to the National Aerometric Data Bank, and used to calculate annual averages and maxima.

5.3.4.1 Staggered high-volume sampler measurements. During episode conditions, the air pollution control agency may find it necessary to inform the public of existing conditions two or three times per day. Therefore, several high-volume samplers could run for 24 hour periods staggered every 4 to 6 hours throughout the episode. The sample could be weighed immediately, and that weight used in deciding what action should be taken concerning the possible emergency. Then the filter would be equilibrated for 24 hours and reweighed.

5.3.4.2 Alternative measurements. The paper tape sampler and the integrating nephelometer can be used to indicate the need for overlapping high-volume sampler measurements. The paper tape sampler has been used in most previous indices and has both Federal Episode

Criteria and a Significant Harm Level. The Coefficient of Haze (COH) value from the paper tape sampler, however, is poorly correlated with TSP levels. In addition, the paper tape sampler has not been determined to be an "equivalent method" to the FRM. Therefore, its use should be limited to index reporting and must not be used to determine compliance with the NAAQS for particulate matter.

A newer instrument relatively untested in routine field applications is the integrating nephelometer. It measures the scattering of light from small particles and correlates well with visibility and TSP measurements. Both the paper tape sampler and the nephelometer can produce a running 24-hour value which can be used as a qualitative indicator of TSP loadings in the atmosphere.

5.3.5 Frequency of Reporting and Appropriate Averaging Times. The frequency of reporting is left up to the agency, within these suggested ranges. It may be desirable to report the index once a day but probably not more than three times per day. Because the high-volume sampler has a 24-hour averaging period, agencies might consider operating two or more high-volume samplers at the same station but with off-set time periods, ending between 8 a.m. and 6 p.m. to provide reporting information during the most desirable period.

If the agency desires, the paper tape sampler or integrating nephelometer could be used in conjunction with the high-volume sampler to provide estimates of the most recent ambient particulate loading. Thus used, the paper tape sampler provides some guidance on whether or not to undertake more intensive measurements during high air pollution levels.

Appropriate averaging times for which the index should be tabulated and reported for each pollutant are:

TSP—TSP values taken with the high-volume sampler are discrete 24-hour values. Monitoring the data collection should be on a schedule consistent with the agency's need to report the air quality index. Other overlapping times may be employed by those agencies wishing to report more than one index value per day.

SO₂—The suggested reporting value is the most current 24-hour running average since the last reporting period.

CO—Although there are two standards for CO (8 hours and 1 hour), the 8-hour standard is usually considered the limiting one and will be the one violated in the vast majority of cases. The most current 8-hour running average since the last reporting should be used. In addition, the agency could also report the index value associated with the highest 8-hour average during the reporting period.

O₃—The suggested reporting value for O₃ is the highest hourly value since the last reporting period. The reporting periods are usually 24 hours or shorter.

NO_x—Although the standard for NO_x is an annual one, there are hourly values

associated with episode criteria; therefore, using the highest hourly value since the last reporting period is recommended.

8. REFERENCES

1. Thom, Gary, and Wayne R. Ott. Compendium Analysis, and Review of United States and Canadian Air Pollution Indices, joint study by the U.S. Environmental Protection Agency and the Council on Environmental Quality, December 1975.
2. FEDERAL REGISTER, Vol. 36, April 30, 1971, pp. 8186-8201.
3. FEDERAL REGISTER, Vol. 36, November 25, 1971, pp. 22390-22414.
4. FEDERAL REGISTER, Vol. 36, December 17, 1971, p. 24002.
5. FEDERAL REGISTER, Vol. 36, March 13, 1974, p. 9672.
6. FEDERAL REGISTER, Vol. 40, August 20, 1975, pp. 36330-36333.
7. Ott, Wayne R. and William F. Hunt, Jr. "A Quantitative Evaluation of the Daily Air Pollution Index Proposed by the U.S. Environmental Protection Agency." Presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, Oregon, June 1976.
8. Hunt, William F., Jr., and Wayne R. Ott. Pollutant Standards Index (PSI) Evaluation Study, Joint Office of Air and Waste Management and Research and Development Report, U.S. Environmental Protection Agency, April 1976.
9. Hunt, William F., Jr., William M. Cox, Wayne R. Ott, and Gary Thom. A Common Air Quality Reporting Format, Precursor to an Air Quality Index, presented at the Fifth Annual Environment Engineering and Science Conference, Louisville, Kentucky, March 3-4, 1975.
10. Air Quality Criteria for Particulate Matter, USDHEW, PHS, CPEHS, NAPCA, Washington, D.C., January 1969, No. AP-49.
11. Air Quality Criteria for Sulfur Oxides, USDHEW, PHS, CPEHS, NAPCA, Washington, D.C., January 1969, No. AP-50.
12. Air Quality Criteria for Carbon Monoxide, USDHEW, PHS, CPEHS, Washington, D.C., March 1970, No. AP-62.
13. Air Quality Criteria for Photochemical Oxidants, USDHEW, PHS, CPEHS, Washington, D.C., March 1970, No. AP-63.
14. Air Quality Criteria for Nitrogen Dioxide, EPA, APCO, Washington, D.C., January 1971, No. AP-84.
15. Thom, G. C. and W. R. Ott. Atmospheric Environment, 10, 261 (1976).
16. Thom, G. C., W. R. Ott, W. F. Hunt, and J. B. Moran. "A Recommended Standard Air Pollution Index," presented at 171st National Meeting of the American Chemical Society, New York, N.Y., April 1976.
17. Knelson, John H., U.S. Environmental Protection Agency, memorandum to Raymond Smith, U.S. Environmental Protection Agency, December 15, 1975.
18. National Weather Service, Operations Manual, Air Pollution Weather Forecasts, WSOM Issuance 75-13, Part C, Chapter 30, April 1975.
19. National Weather Service, Technical Procedures Bulletin No. 122: Air Stagnation Guidance for Facsimile and Teletype (3rd Edition), October 21, 1974. (Supersedes previous TPB's Nos. 52, 58, and 69).
20. FEDERAL REGISTER, Vol. 40, February 18, 1975, pp. 7049-7070.
21. Helms, G. F. U.S. Environmental Protection Agency, Region IV, Atlanta, Georgia. Personal communication, December 1975.

APPENDIX A

INFORMATION NEEDS FOR FORECASTING PSI

Introduction

The information needed to qualitatively forecast the Pollutant Standards Index (PSI) is of two types: (1) pollutant-related and (2) meteorological. The pollutant-related information may include data on source locations, physical source characteristics and emissions, atmospheric-physicochemical transformation processes, and actual air quality measurements and trends. Meteorological information that may be included are data on synoptic weather features, on meteorological parameters indicative of the dispersive capability of the lower atmosphere, and of the photochemical potential. It might also include information on the effect of local terrain complexities upon meteorological parameters. Together, pollutant-related and meteorological information form the input to locally tailored predictive techniques such as mathematical models, statistically derived methods, or other techniques that may be applied along with subjective judgment to some degree.

The necessary pollutant-related information is to be obtained by the air pollution control (APC) agency having local responsibility for issuing the Index. The National Weather Service (NWS) is the primary agency supplying the needs of APC agencies for meteorological information. NWS services include issuance of advisories on air pollution potential and air stagnations. However, some APC agencies and/or their consultants may also collect and interpret meteorological information to supplement that available from the NWS.

General data needs

The types and amounts of pollutant-related information needed will vary depending on the particular pollutant(s) of concern and the source to monitoring site configurations in the particular geographical area. For example, in the Los Angeles Basin, photochemical oxidant is the primary pollutant of concern and since precursor sources (mainly mobile) are widespread, the potential for maximum impact exists over a rather large area. In contrast, in Pittsburgh and Birmingham where suspended particulate matter from industrial ferrous emissions will most likely cause elevated pollutant levels, the maximum impact will probably be more localized; thus, pollutant-related information may not have to be as extensive. It is also important to know the diurnal, weekly, and seasonal characteristics of emissions. For instance, carbon monoxide concentrations are closely associated both spatially and temporally with automobile emissions. Typical diurnal patterns reflect morning and evening peaks in vehicular traffic. High concentrations may shift weekly in response to changes in workday versus weekend automotive travel patterns. Seasonal patterns may shift in some areas with vacation travel.

Generally, an up-to-date emissions inventory should be available for communities where PSI is to be utilized in order to adequately assess the source to monitoring site impact relationships. For point sources (usually > 100 tons/year of a pollutant), information should include the source location, pollutants emitted, emission rates, and stack parameters. Area source data, including lesser point emissions, are not normally as specific. Available area emissions, in tons per year, are usually quantified by city or county. Vehicular emissions may be estimated by combining local traffic pattern information

with documented vehicle-fleet emissions rates. These emissions data are available from the EPA National Emissions Data System (NEDS), state planning agencies, and private sources. It may be necessary to supplement these data with emissions information affecting the various temporal cycles; for instance, information on the normal operating schedules of large point sources and on traffic volume cycles in congested areas.

Trends in the concentrations of pollutants can also be useful in predicting the PSI. Trend information might include the day-to-day variation in peak hourly values or 24-hour averages. Trends data should always be evaluated relative to changes taking place or anticipated in emissions or meteorology. Persistence of a trend would especially aid in arriving at the PSI forecast if no definitive changes in emissions or meteorological features are indicated. Interpretations of trends information, on a day-to-day basis, require care and experience because of the fluctuations that for varied reasons tend to occur about a mean trend.

The types of meteorological information that could be used for forecasting the PSI have been rather well defined through past experience with forecasting methods developed in support of air pollution control activities. This support has largely dealt with forecasting indices and episodic conditions. The meteorological features and parameters that are most often utilized in forecasting air quality indices at the present time are:

- Character and movement of air masses and fronts
- Areas of air mass subsidence
- Incidence, intensity, and height of inversions
- Mixing layer height
- Prevailing wind direction
- Mean wind speed (surface and mixing layer)
- Ventilation (mixing layer mean wind speed x mixing height)
- Precipitation
- Temperature
- Total sky cover

Of course, the emphasis placed on particular features and parameters listed above will vary with location and pollutant(s) of concern.

NWS information and support services

The NWS operates a comprehensive Air Pollution Weather Forecast Program. The program is administered from NWS National and Regional Headquarters with operational program elements at the National Meteorological Center (NMC) and local Weather Service Forecast Offices (WSFO's). Details of the program are contained in the NWS Operations Manual¹ and Technical Procedures Bulletins.² This program generates a variety of national, regional, and local air pollution weather forecast products which are issued to the public, to control agencies, or to both, as appropriate.

The NMC is responsible for providing the large-scale meteorological guidance used by field offices in the preparation of advisories and other products which are particularized and tailored to specific geographic areas to user requirements.

The air pollution weather products of NMC are comprised of the following elements:

- a. *Forecast air stagnation charts.* Issued every morning on facsimile, these four panel computer based charts depict expected areas of atmospheric stagnation (Figure 1).
- b. *Air stagnation narrative.* This plain language teletype message describing the Air Stagnation Charts, is issued every morning.

See footnotes at end of appendix.

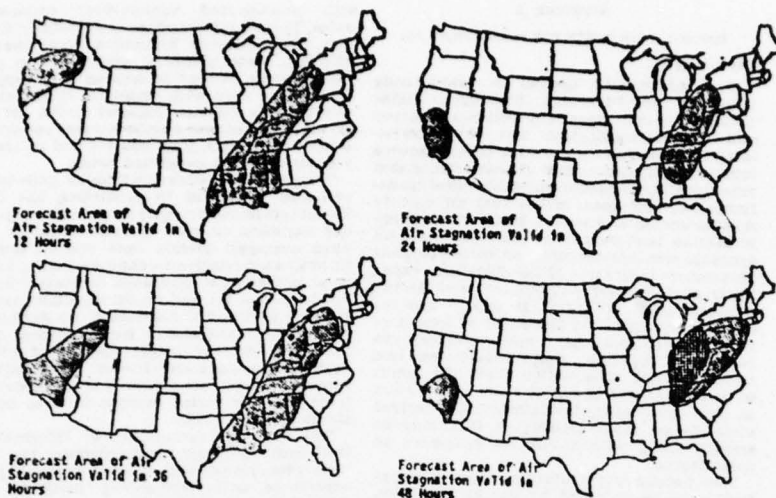


Figure 1. Sample of Stagnation Chart sent on facsimile, depicting significant areas of large-scale stagnation. Shaded area indicates area of large-scale stagnation, hatched area indicates area that is under large-scale stagnation on all four panels.

c. *Air stagnation data.* This computer derived teletype message currently consists of today's mixing height and transport wind speeds for selected NWS stations.

The WSFO's have responsibility for local forecast products within designated geographic boundaries, including the issuance of the following three basic air pollution products:

a. *Air stagnation advisories (ASA).* Issued to the public and control agencies when locally established critical values of transport wind, mixing height, and ventilation are forecast to be reached and conditions are expected to persist for at least 36 hours, causing probable significant decrease in air quality.

b. *Special dispersion statements.* A special product issued only to control agencies when a potential air pollution situation is determined by an NWS forecaster to exist but no ASA will be issued because such an issuance would not be in the public interest.

c. *Dispersion outlooks.* A routine product issued by all WSFO's where it has been deter-

mined that the APC needs routine meteorological information to facilitate day-to-day operations and adequate manpower is available at the WSFO. The format, content, and issuance times of this product is determined by the WSFO and APC. The Dispersion Outlook is issued only to the APC.

Occasionally, air pollution episodes of public concern may occur during non-stagnant situations. These involve pre-designated episode levels that require control actions to improve the air quality condition. In these situations, the WSCC provides the appropriate government agencies with the meteorological support necessary for pollution control or abatement procedures.

In conjunction with these services, the NWS provides supplemental, low-level upper air soundings at designated stations. This program which provides for greater spatial and temporal detail on dispersion conditions, especially during episodes or potential episodes, is available for several cities. These locations are listed below, together with the sounding scheduled:

Location:	Program
Birmingham, Ala.	1/day routine week day, weekend and 2d daily observation call.
Charleston, W. Va.	1/day routine week day, weekend and 2d daily observation call.
Chicago, Ill.	1/day routine week day, weekend and 2d daily observation call.
El Monte, Calif.	2/day routine week days except occasionally omit afternoon soundings on well ventilated days.
Houston, Tex.	1/day routine week day, weekends and 2d daily sounding on call.
Los Angeles, Calif.	2/day, 7 days a week.
Philadelphia, Pa.	All observations on call.

Additionally, special low-level soundings are available on an on-call basis at the regular upper air observation facilities near Denver, Colo., New York, N.Y., Oakland, Calif., Pittsburgh, Pa., and Washington, D.C. An aircraft sounding is available at Sacramento, Calif. Through a Cooperative effort, state APC agencies take soundings as needed in Seattle, Boston, Portland, Oreg., and San Jose, Ga. These are taken at special facilities that were established by the NWS.

The NWS has, up until recently, not been too closely involved nationwide in predicting conditions conducive to buildup of photochemical pollutants. Because of recent interest and increasing demand for such information, the NWS is in the process of evaluating possible techniques with the objective of modifying or adding to current air pollution weather forecast products and services.

Development of prediction methodology

The available services and information briefly described above form the basis for developing a local community procedure for making local qualitative forecasts of the PSI. These forecasts can be reasonably made for periods up to a day in advance in terms of No Significant Change, Increase, or Decrease. It is advisable for agencies planning to use the index along with a forecast procedure to have personnel on their staffs familiar with meteorological data and how these data may be applied in development of index prediction methodology.

Considering the wealth of information available from the NWS, it seems logical that the issuance of an index forecast should be scheduled at intervals complementary to operations at the NWS. This would allow the APC agency to have the advantage of the most current NMC weather products and WSFO air pollution forecast services. In addition, it would encourage further cooperation and support of the local NWS facility. However, while it can be expected that NWS meteorologists will be able to closely coordinate with a local agency in arriving at index change predictions during potential or actual episodic conditions, they will most likely not be able to give such attention to routine day-to-day forecasting of the index. Also, NWS personnel would not be expected to have detailed knowledge of pollutant-related factors.

Where an APC agency may have developed the expertise necessary to make quantitative predictions of the PSI for the following day, they should be encouraged to make these predictions. However, it should be cautioned that making quantitative predictions of air quality or air quality indices should not be attempted without a reasonable expectation of success based on well-tested techniques. Otherwise, a less than satisfactory forecast record could result, which would tend to have an adverse effect on public acceptance of the PSI.

Mathematical air quality simulation models have to date not been used to any appreciable extent in index prediction. Because of their relative complexity, cost of modifying for local use, and time and expense that may be involved in making day-to-day predictions, their use for predicting the index qualitatively will initially be limited. However, where APC agencies may progress to the point of making quantitative forecasts, the use of models may become necessary. A listing and brief description of possible air quality models that could be applied are contained on OAGPS Guideline No. 1.2081.²

Current use of meteorological information in index prediction

Approximately half of the 25 local agencies currently issuing air pollution indices make forecasts of their index a day in advance. Of these, only one third have meteorologists on their staffs, while the remainder rely upon NWS meteorologists for interpretation of meteorological data. Three of the local agencies were selected to serve as examples of how varying degrees of meteorological information can be incorporated into air quality index forecasting.

One of the more sophisticated forecast techniques, the Air Pollution Dispersion Index, was developed six years ago by the State of Colorado Department of Health in Denver.⁴ A forecast is issued each morning for four time periods, a.m. today, p.m. today, a.m. tomorrow, and p.m. tomorrow. The technique developed by department meteorologists is based upon concepts of mixing heights and wind speed discussed by Holzworth in AP-101,⁵ and employs a nomogram of wind speed vs. mixing heights, with isolines of

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constant ventilation factor values serving to demarcate four dispersion categories. These categories are:

Ventilation factor ($m^3/sec.$) (wind speed \times mixing height)	
Associated dispersion	
<2,000	Bad.
>2,000 to 4,000	Fair.
>4,000 to 6,000	Good.
>6,000	Excellent.

The mixing heights used for the "today" forecast are determined from a plot of the Denver morning upper air sounding, the morning minimum surface temperature at Stapleton Airport plus 3° to 4° C, and the forecast afternoon maximum temperature. The "tomorrow" mixing heights are determined from the forecast 24-hour minimum and 36-hour maximum temperature, and a forecast of the sounding using locally-tailored analytical techniques. All transport wind speeds are derived from either observed or forecast NWS data. Critical factors in Denver are the typical low-level morning inversions which serve to deteriorate air quality and the occurrence or forecast of rain or snow which automatically leads to a forecast of improving air quality.

The City of Philadelphia Department of Public Health³ uses general meteorological conditions and a NWS Air Stagnation Index to predict the Philadelphia Air Quality Index. The local agency receives meteorological information twice daily from the Philadelphia NWS office. Parameters of most concern are wind speed, gustiness and the likelihood of a frontal passage with its associated turbulent mixing. Wind direction is not a vital concern since emission sources in the city are relatively well distributed in all directions. Specifically, the Air Stagnation Index is formulated from the algebraic sum of several weighted meteorological parameters as shown in Table 1. To determine the index value, the weights associated with each observed parameter are summed. When at least one of the meteorological values is associated with a "Stop," excellent dispersion is forecast. Otherwise, dispersion is forecast according to the following scheme:

Sum of weights:	Forecast dispersion
-1, -2, -3	Good.
0	Marginally good.
+1	Marginally poor.
+2, +3	Poor.

TABLE 1. Air Stagnation Check Sheet¹

Meteorological parameters	Value categories	Weights
morning wind speed (knots)	> 10 ≤ 10 > 5 ≤ 5	STOP -1 +1 +2
afternoon and evening wind speed (knots)	> 11 ≤ 11 > 5 ≤ 5	STOP -1 +1 +2
morning mixing height (meters)	> 1500 ≤ 1500 > 750 ≤ 750	STOP -1 0
afternoon ventilation factor (meter ³ /sec)	> 8000 ≤ 8000 > 4000 ≤ 4000	STOP -2 0 +1

³Philadelphia Forecast Office
National Weather Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

However, due to the nature of the Philadelphia Air Quality Index, a dramatic change in dispersion is required to effect a change in the index values.

The Department of Public Health in Dallas⁴ uses meteorological data in a very qualitative manner. The general weather situation is examined daily with primary importance directed toward stagnating high pressure systems, cold frontal passages, and prevailing wind direction. NMC trajectory analysis data, surface weather patterns, and prognostic charts are used in a non-rigorous manner. For example, geographical plots of smoke and haze reports are occasionally used to determine the area extent and approach of pollutants due to large scale circulation patterns.

Improving conditions are forecast with the occurrence of precipitation, a frontal passage, and increasing wind speed. Deteriorating air quality is predicted when trajectories persist from local or more distant sources or sources areas.

Dated: August 27, 1976.

ROGER STREETLOW,
Assistant Administrator
for Air and Waste Management.

REFERENCES

1. National Weather Service, Operations Manual, Air Pollution Weather Forecasts, WSOM Issuance 75-13, Part C, Chapter 30, April 1975.
2. National Weather Service, Technical Procedures Bulletin No. 122: Air Stagnation Guidance for Facsimile and Teletype (3rd Edition), October 21, 1974. (Supersedes previous TPB's Nos. 52, 58, and 69.)
3. U.S. Environmental Protection Agency, Guidelines for Air Quality Maintenance Planning and Analysis, Volume 12: Applying Air Quality Models to Air Quality Maintenance Areas, EPA-450/4-74-012, September 1974 (OAOQPS No. 1.2-031), Research Triangle Park, N.C.
4. Thom, G., and Wayne R. Ott, "Compendium Analysis, and Review of United States and Canadian Air Pollution Indices," Joint Study by the U.S. Environmental Protection Agency and the Council on Environmental Quality, Washington, D.C., December 1975.
5. Holzworth, G. C., "Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States," U.S. Environmental Protection Agency, Research Triangle Park, N.C. January 1972 (AP-101).

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APPENDIX IV

CONTROL OF AIR POLLUTION
FROM AIRCRAFT AND AIRCRAFT ENGINES
(40 C FR 87)

Title 40—Protection of Environment

Subpart B—Engine Fuel Venting Emissions (New and In-Use Aircraft Gas Turbine Engines)

- Sec.
87.10 Applicability.
87.11 Standard for fuel venting emissions.
87.12 Sampling and instrument checks.
87.13 Test run.

Subpart C—Exhaust Emissions (New Aircraft Gas Turbine Engines)

- 87.20 Applicability.
87.21 Standards for exhaust emissions.
87.22 Test run.

Subpart D—Exhaust Emissions (In-Use Aircraft Gas Turbine Engines)

- 87.30 Applicability.
87.31 Standards for exhaust emissions.
87.32 Test run.

Subpart E—Exhaust Emissions (New and In-Use Aircraft Piston Engines)

- 87.40 Applicability.
87.41 Standards for exhaust emissions (new aircraft piston engines).
87.42 Standards for exhaust emissions (in-use aircraft piston engines).

Subpart F—Exhaust Emissions (New and In-Use Aircraft)

- 87.50 Applicability.
87.51 Standards for exhaust emissions (new aircraft).
87.52 Standards for exhaust emissions (in-use aircraft).

Subpart G—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft and Aircraft Gas Turbine Engines)

- 87.60 Introduction.
87.61 Turbine fuel specifications.
87.62 Test procedure (propulsion engines).
87.63 Test procedure (auxiliary power units).
87.64 Sampling and analytical system for measuring exhaust emissions.
87.65 Information to be recorded.
87.66 Calibration and instrument checks.
87.67 Sampling procedures.
87.68 Test run.
87.69 Chart reading.
87.70 Calculations.
87.71 Compliance with emission standards.

Subpart H—Test Procedures for Engine Smoke Emissions (Aircraft Gas Turbine Engines)

- 87.80 Introduction.
87.81 Fuel specifications.
87.82 Sampling and analytical system for measuring smoke exhaust emissions.
87.83 Information to be recorded.
87.84 Calibration and instrument checks.
87.85 Test run.
87.86 Determination of SN.
87.87 Calculations.
87.88 Compliance with emission standards.

Subpart I—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft Piston Engines)

- 87.90 Introduction.
87.91 Gasoline fuel specifications.
87.92 Test procedure.

PART 87—CONTROL OF AIR POLLUTION FROM AIRCRAFT AND AIRCRAFT ENGINES

Subpart A—General Provisions

- Sec.
87.1 Definitions.
87.2 Abbreviations.
87.3 General requirements.
87.4 Test conditions.
87.5 Special test procedures.
87.6 Aircraft safety.

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§ 87.1

certified on or after the effective date of the applicable emission standard.

- (10) "Rated power" means the maximum power/thrust available for take-off at standard day conditions as approved for the engine by the Federal Aviation Administration.
(11) "Standard day conditions" means standard ambient conditions as described in the United States Standard Atmosphere, 1962 (i.e., temperature=59°F, relative humidity=0%, and pressure=29.92 inches Hg).

- (12) "Power setting" means the power output of an engine in terms of pounds thrust for turbojet and turbofan engines and shaft horsepower for turboprop and piston engines.
(13) "Pound-thrust/hr." means pounds of thrust for 1 hour.
(14) "Shaft horsepower" means only the measured shaft power output of an auxiliary power unit, turboprop, or piston engine.

- (15) "Auxiliary power unit" means any engine installed in or on an aircraft exclusive of the propulsion engines.
(16) "Class T1" means all aircraft turbofan or turbojet engines except engines of Class T3 of rated power less than 8,000 pounds thrust.

- (17) "Class T2" means all turbofan or turbojet aircraft engines except engines of Class T3, T4, and T5 of rated power of 8,000 pounds thrust or greater.

- (18) "Class T3" means all aircraft gas turbine engines of the JT3D model family.

- (19) "Class T4" means all aircraft gas turbine engines of the JT8D model family.

- (20) "Class T5" means all aircraft gas turbine engines employed for propulsion of aircraft designed to operate at supersonic flight speeds.

- (21) "Class P1" means all aircraft piston engines, except radial engines.

- (22) "Class P2" means all aircraft turboprop engines.

- (23) "Taxi/Idle (in)" means those aircraft operations involving taxi and idle between the time of landing roll-out and final shutdown of all propulsion engines.

- (24) "Taxi/Idle (out)" means those aircraft operations involving taxi and idle between the time of initial starting of the propulsion engine(s) used for the taxi and turn onto duty runway.

- (25) "Exhaust emissions" means substances emitted to the atmosphere from the exhaust discharge nozzle of an aircraft or aircraft engine.

Sec. 87.93 Sampling and analytical system for measuring exhaust emissions.

- 87.94 Information to be recorded.
87.95 Calibration and instrument checks.
87.96 Sampling procedures.
87.97 Test run.
87.98 Chart reading.
87.99 Calculations.
87.100 Compliance with emission standards.

Subpart J—Temporary Exemption From Aircraft Emission Standards (Fuel Venting and Smoke)

- 87.101 Application for temporary exemption.
87.102 Thirty-day suspension of fuel venting and smoke standards.

Appendix A—Instrumentation (Aircraft Gas Turbine Engine Measurements)

Appendix B—Instrumentation (Aircraft Piston Engine Measurements)

Authority: Sec. 231 of the Clean Air Act, as amended (42 U.S.C. 1857f-9, 1857(f), 1857(g)).

Source: 38 FR 10090, July 17, 1973, unless otherwise noted.

Subpart A—General Provisions

§ 87.1 Definitions.

- (a) As used in this part, all terms not defined herein shall have meaning given them in the Act:

- (1) "Act" means the Clean Air Act, as amended by Public Law 91-604.

- (2) "Administrator" means the Administrator of the Environmental Protection Agency to whom the authority involved may be delegated.

- (3) "Aircraft" means any airplane for which a U.S. standard airworthiness certificate or equivalent foreign airworthiness certificate is issued.

- (4) "Aircraft engine" means : propulsion engine which is installed in or on an aircraft.

- (5) "Aircraft gas turbine engine" means a turbofan, turbojet, or turboprop engine.

- (6) "New aircraft gas turbine engine" means an aircraft gas turbine engine which has never been in service.

- (7) "New aircraft piston engine" means an aircraft piston engine which has never been in service.

- (8) "In-use aircraft gas turbine engine" and "in-use aircraft piston engine" mean an aircraft gas turbine engine or aircraft piston engine (as appropriate) which is in service.

- (9) "Newly certified aircraft gas turbine engine" means an aircraft gas turbine engine which is originally type

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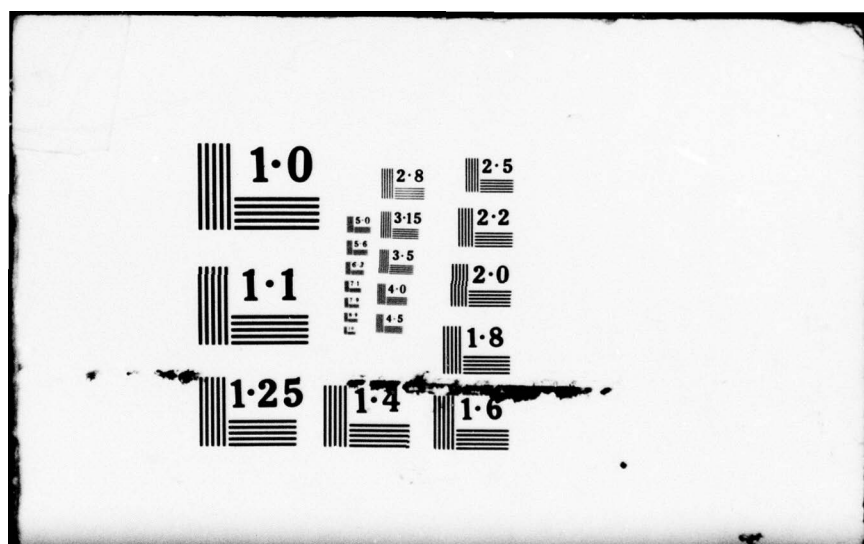
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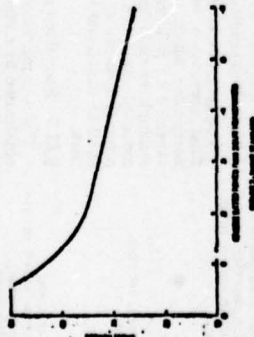
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(4) Class T4:

(i) Hydrocarbons	4.9 pounds/1,000 horsepower-hours/cycle
(ii) Carbon monoxide	26.8 pounds/1,000 horsepower-hours/cycle
(iii) Oxides of nitrogen	12.9 pounds/1,000 horsepower-hours/cycle
(iv) Smoke	Smoke number from Figure 2.

(4) The smoke number for each engine shall be determined by obtaining the smoke number corresponding to the engine rated power from Figure 1 for turbofan or turbojet engines and Figure 3 for turboprop engines.

(i) Hydrocarbons	0.4 pound/1,000 pound-thrust hours/cycle
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(4) The standards set forth in paragraphs (a), (b), (c), (d), and (e) of this section refer to a composite gaseous emission sample representing the operating cycles set forth in the applicable sections of Subpart G of this part, and exhaust smoke emissions emitted during operations of the engine as specified in the applicable sections of subpart II of this part, and measured and calculated

graph (a), (b), (c), and (e) of this section shall be the test program to determine the conformity of new and in-use aircraft gas turbine engines with the applicable standards set forth in this part. The procedures shall also be used to determine emissions from auxiliary power units in determining conformity of new and in-use aircraft with the applicable standards set forth in this part.

(b) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of Class T4, beginning January 1, 1974, shall not exceed: Smoke number of 30.

(b) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of class T2 and of rated power of 29,000 pounds thrust or greater, beginning January 1, 1976, shall not exceed: Applicable smoke number from Figure 1.

(c) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of class T3, beginning January 1, 1978, shall not exceed: Smoke number of 25.

(b) The standards set forth in paragraphs (a), (b), and (c) of this section refer to exhaust smoke emissions emitted during operations of the engine as specified in the applicable sections of Subpart H of this part, and measured and calculated in accordance with the procedures set forth in this subpart.

(e) In addition to the requirements imposed by paragraphs (a), (b), and (c) of this section, each in-use aircraft gas turbine engine shall not exceed the level of the emissions applicable to such engine when it was new.

Subpart E—Exhaust Emissions (New and In-Use Aircraft Piston Engines)

§ 87.40 Applicability.
The provisions of this subpart are applicable to all aircraft piston engines of class F1 beginning on the date specified, exceed:

(ii) Carbon monoxide	8 pounds/1,000 pound-thrust hours/cycle
(iii) Oxides of nitrogen	3 pounds/1,000 pound-thrust hours/cycle
(iv) Smoke	Smoke number from Figure 1.

Subpart F—Exhaust Emissions (New and In-Use Aircraft)

§ 87.50 Applicability.

The provisions of this subpart are applicable to all aircraft beginning on the date specified.

§ 87.51 Standards for exhaust emissions (new aircraft).

(a) Exhaust emissions resulting from the generation of onboard power from each new aircraft manufactured on or after January 1, 1978, shall not exceed:

(i) Hydrocarbons	0.4 pound/1,000 hp.-hr. of power output
(ii) Carbon monoxide	8 pounds/1,000 hp.-hr. of power output
(iii) Oxides of nitrogen	3 pounds/1,000 hp.-hr. of power output

Subpart G—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft and Aircraft Gas Turbine Engines)

§ 87.60 Introduction.

Except as provided under § 87.5, the procedures described in this subpart shall be the test program to determine the conformity of new and in-use aircraft gas turbine engines with the applicable standards set forth in this part. The procedures shall also be used to determine emissions from auxiliary power units in determining conformity of new and in-use aircraft with the applicable standards set forth in this part.

(a) The test consists of operating the engine at prescribed power settings on an engine dynamometer (for engines producing primarily shaft horsepower) or thrust measuring test stand (for engines producing primarily thrust). The

exhaust gases generated during engine operation are sampled continuously for specific component analysis through the analytical train.

(b) The ethanolamine test is designed to measure hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen concentrations and determine nitrogen concentrations and engine work output through calculations during a simulated aircraft landing-takeoff cycle (LTO). The LTO cycle is based on time in mode data during high activity periods at major airports. The test for propulsion engines consists of at least the following five modes of engine operation: Taxi/Idle (out), takeoff, climbout, approach, takeoff/take (in). The mass emission and work output for the modes are combined to yield the reported values. The test for auxiliary power units consists of one mode: Full load.

(c) When an engine is tested for exhaust emissions on an engine dynamometer or test stand, the complete engine shall be used with all accessories which might reasonably be expected to influence emissions to the atmosphere in actual use and functioning but excluding auxiliary gearbox-mounted components required to drive aircraft systems and service air bleed.

§ 87.61 Turbine fuel specifications. For exhaust emission testing, fuel meeting the specifications. ASTM D1655-latest version-Jet A, shall be used. Non-metallic additives as specified in ASTM D1655-latest version-Jet A may be present. Additives used for the purpose of smoke suppression (such as organo-metallic compounds) shall not be present.

§ 87.62 Test procedures (propulsion en-

(a) (1) The engine shall be tested in each of the following five engine operating modes which simulate aircraft

Actual power setting, that when corrected to standard day conditions, corresponds to the following percentage of rated power.

<i>Mode</i>	<i>Class T₁ or P₁</i>	<i>Class T₂ T₂ or P₂</i>
<i>Traffic (cont)</i>	<i>See subparagraph (2) of this paragraph.</i>	
<i>T-leaf</i>	100.....	100
<i>Climb</i>	90.....	80
<i>Approach</i>	90.....	80
<i>Traffic (in)</i>	<i>See subparagraph (2) of this paragraph.</i>	

(2) The taxi/idle operating modes shall be carried out at a power setting in accordance with applicable Federal Aviation Administration regulations, at the manufacturer's recommended power setting for idle.

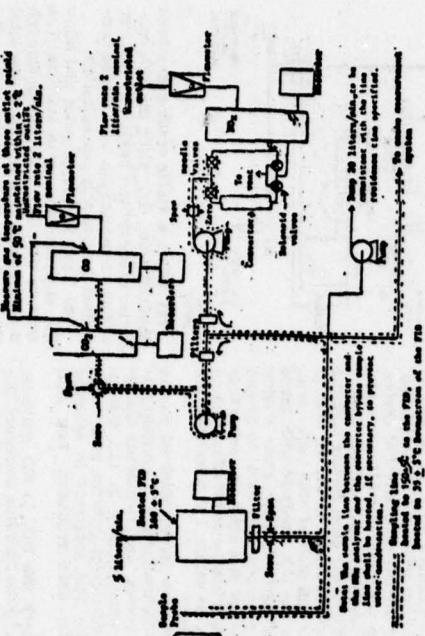
(b) Emission testing shall be conducted on warmed-up engines which have achieved a steady operating temperature.

§ 87.63 Test procedure (auxiliary power units)

(a) In determining compliance with the aircraft emission standards under Subpart P of this part, each auxiliary power unit shall be tested at its maximum load condition as indicated by its power output, exhaust gas temperature, or turbine inlet temperature to determine its mass emission rate and work output. The work output shall be determined as a combination of shaft energy contained and actual bleed air energy consumed. The bleed air equivalent horsepower for APU's shall be determined as follows:

Work Output = 0.341W ($T_{1,2,3,4} - T_{1,2}$), where
W = bleed airflow in lbs./sec, $T_{1,2,3,4}$ = measured
bleed air temperature in °F, and T = com-
pressor inlet temperature in °F.

(b) Emission testing shall be conducted on warmed-up auxiliary power units which have achieved a steady operating temperature.



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(c) In determining compliance with the aircraft emission standards under Support P of this part, auxiliary power units shall be tested prior to installation. If the effect is greater than 2 percent measured CO levels, all subsequent measurements shall be corrected for these interferences.

(a) Schematic drawing. Figure 3 is a sampling and analytical system for measuring exhaust emissions.

(1) *Sampling probe.* (i) Probe design concept: The probe shall be made of stainless steel. If a mixing probe is used, all sampling holes shall be of equal diameter. Total probe orifice area shall be such that the principal pressure drop (at least 80 percent) through the probe assembly shall be taken at the orifice (or orifices).

(ii) Probe orientation and sampling

(b) **Water removal devices.** No desiccants, dryers, water traps, or related location:

shall be used. Either mixing or individual probes are acceptable.

(b) A minimum of three different radial positions shall be used in each instrument configuration.

such that condensation is avoided

(c) A minimum of 12 sampling points is used, the points in circumference of the instrument. The extent of water vapor and carbon dioxide interference is not a problem.

erence on the carbon monoxide analyzer shall be determined by passing a range of equally adjacent sampling areas shall be separated by at least 80° angular dis-

of known concentrations of carbon fluoride and water vapor through the placement. No two sampling points shall be separated in any direction by a dis-

instrument and observing the response. tance less than 0.1 tailpipe radius or 0.1

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the reading of (11) indicating whether the NO contains any NO.
Calculate the efficiency of the NO_x analyzer by substituting the concentration obtained during the test into the following equation:

$$\% \text{Eff} = \frac{(a) - (1b)}{(a) - (1a)} \times 100\%$$

The efficiency of the converter should be greater than 90 percent. Adjusting the converter temperature may be needed to maximize the efficiency. Efficiency checks should be made on each analyzer range using an NO span gas concentration appropriate to the instrument range.

(viii) If the converter efficiency is not greater than 90 percent, the cause of the inefficiency shall be determined and corrected before the instrument is used.

(ix) The converter efficiency shall be checked at least once weekly and preferably once daily.

(b) Verifications and instrument checks shall be performed in accordance with § 87.67 on in-use systems. Verification and instrument checks shall be performed before and after each test, but not less than once per hour.

(c) For the purposes of this section, the term "zero grade air" includes artificial "air" consisting of a blend of nitrogen and oxygen with oxygen concentrations between 18- and 21-mole percent.

(10) 728 10000, July 17, 1973, as amended at 50 FR 54724, Dec. 18, 1973

§ 87.67 Sampling procedures.

(a) HC, CO, CO₂, and NO_x measurements. Allow a minimum of 2 hours warmup for the CO, CO₂, HC, and NO_x analyzers. (Power is normally left on infrared and chemiluminescence analyzers, but when not in use, the chopper motors of the infrared analyzers are turned off and the phototube high voltage supply of the chemiluminescence analyzer is placed in the standby position.) The following sequence of operations shall be performed in conjunction with each series of measurements:

(1) Check the sampling system for any leaks that could dilute the exhaust gas and replace or clean sample line filters.

(2) Introduce the zero grade gas at the same flow rates used to analyze the test samples and zero the analyzers. Obtain a stable zero on each amplifier meter and recorder. Recheck after tests.

(3) Introduce span gases and set the CO and CO₂ analyzer gains, the HC analyzer sample capillary flow rate and electronic gain control, if provided, and the NO_x analyzer high voltage supply or amplifier gain to match the calibration curves. In order to avoid corrections, span and calibrate at the same flow rates used to analyze the test samples. Span gases should have concentrations equal to approximately 80 percent of each range used. If gain has shifted significantly on the CO or CO₂ analyzers, check tuning. If necessary, check calibration. Respan at least at end of test but not less than once per hour. Show actual concentrations on chart. Log gain readings.

(4) Check zeros; repeat the procedure in subparagraphs (1) and (2) of this paragraph, if required.

(5) Check sample line temperature and sample residence time. To check sample residence time:

(i) Introduce HC span gas into sampling system at sample inlet and simultaneously start timer.

(ii) When HC instrument indication is 15 percent of span concentration, stop timer.

(iii) If elapsed time is more than 2.0 seconds, make necessary adjustments.

(iv) Repeat (i) through (iii) with CO, CO₂, and NO instruments and span gases.

(6) Check instrument flow rates and pressures.

(7) The engine shall be operated in each operating mode until emission levels have stabilized as indicated by a constant instrument reading or recorder output. This stabilized reading shall be recorded and used in calculating mass emission rates as called for in Section 87.70.

(8) Measure HC, CO, CO₂, and NO_x concentrations of the exhaust sample at the various modes called for in § 87.62 or 87.63, as appropriate.

(9) If individual probes are used, the number to be reported (for each component) shall be the arithmetic average of the values obtained at each sampling point. If mixing probes are used, the number to be reported shall be the average of the values of the several probes, giving each probe a weighting factor equal to the number of sample points in that particular probe.

(10) Recheck zero and span points at the end of the test and also at approximately one hour intervals during the

test. If either has changed by ± 2 percent of full scale, the test shall be rerun after instrument maintenance: *Provided*, That if it is impractical to repeat the test, a correction based on an interpolation which is linear with time is acceptable for corrections within ± 4 percent.

(b) *Sample system contamination.* (1) Care shall be taken to avoid loading of the sampling system with raw fuel discharge during engine starting.

(2) When the sample probe is in the exhaust stream and sampling is not in process, a back purge with air or an inert gas may be necessary to protect the probe and sample line from particulate buildup which could affect smoke and hydrocarbon readings. Check sample line for contamination each time the instrument zero and span points are checked. Use the following procedure to check the sample line:

(i) Immediately after instrument zero and span measurements and necessary adjustments are complete, introduce hydrocarbon zero gas near the sample probe. If the instrument zero reading increases by more than 5 percent of the scale in use, the sample line shall be purged or cleaned as required, to bring the zero within limits.

(ii) When the requirements of (i) have been met, introduce hydrocarbon span gas into the inlet of the sampling

HC pounds/1,000 pound-thrust-hr. or 1,000 hp-hr., as appropriate/cycle

(2) Carbon monoxide:
CO pounds/100 pound-thrust-hr. or 1,000 hp-hr., as appropriate/cycle

(3) Oxides of nitrogen:
NO_x pounds/1,000 pound-thrust-hr. or 1,000 hp-hr., as appropriate/cycle

(b) The pollutant mass and work output per mode shall be computed by use of the following formulas:

(i) HC mass/mode = HC emission rate \times T.M.
(ii) CO mass/mode = CO emission rate \times T.M.
(iii) NO_x mass/mode = NO_x emission rate \times T.M.
(iv) Work output of each mode = power (in 1000 pounds thrust of 1000 horse power) \times T.M.

(c) The emission rates for each mode shall be computed by use of the following formula:

$$\text{HC emission rate} = \frac{\text{HC}}{\text{Mass}} \times \frac{(\text{CO}) + (\text{CO}_2) + (\text{HC})}{\text{K}}$$

system. If the instrument span reading is different by more than ± 5 percent from the correct setting for the scale in use, the sample line shall be purged or cleaned, as required, to bring the span within limits.

§ 87.68 Test run.
A test run shall consist of operating the engine in accordance with § 87.62 or 87.63, as applicable. During the test run the engine shall not be operated at a power setting above normal idle power before beginning the test sequence of § 87.62. The engine shall be operated in the sequence called for under these sections, unless an alternate procedure is agreed to in writing by the Administrator before such testing is conducted. If repeat runs at full takeoff power are necessary, they may be conducted after the last idle run in the test sequence.

§ 87.69 Chart reading.
Determine the HC, CO, CO₂, and NO_x concentrations of the exhaust sample during the various modes from the instrument deflections or recordings, making use of appropriate calibration charts.

§ 87.70 Calculations.
(a) The final reported test results shall be computed by use of the following formulas:
(1) Hydrocarbon:

Sum of the HC mass/mode of ea. mode
Sum of the work output of ea. mode

Sum of the CO mass/mode of ea. mode
Sum of the work output of ea. mode

Sum of the NO_x mass/mode of ea. mode
Sum of the work output of ea. mode

(b) The pollutant mass and work output per mode shall be computed by use of the following formulas:

(i) HC mass/mode = HC emission rate \times T.M.
(ii) CO mass/mode = CO emission rate \times T.M.
(iii) NO_x mass/mode = NO_x emission rate \times T.M.
(iv) Work output of each mode = power (in 1000 pounds thrust of 1000 horse power) \times T.M.

(c) The emission rates for each mode shall be computed by use of the following formula:

$$\text{HC emission rate} = \frac{\text{HC}}{\text{Mass}} \times \frac{(\text{CO}) + (\text{CO}_2) + (\text{HC})}{\text{K}}$$

§ 87.71 Title 40—Protection of Environment

$$\text{CO emission rate} = \frac{(\text{CO})}{\text{M}_{\text{CO}} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO})}{\text{M}_{\text{CO}} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO})}{\text{M}_{\text{CO}} \cdot \frac{1}{\text{hr}}}$$

$$\text{CO}_2 \text{ emission rate} = \frac{(\text{CO}_2)}{\text{M}_{\text{CO}_2} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO}_2)}{\text{M}_{\text{CO}_2} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO}_2)}{\text{M}_{\text{CO}_2} \cdot \frac{1}{\text{hr}}}$$

$$\text{CO emission rate} = \frac{(\text{CO})}{\text{M}_{\text{CO}} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO})}{\text{M}_{\text{CO}} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO})}{\text{M}_{\text{CO}} \cdot \frac{1}{\text{hr}}}$$

$$\text{CO}_2 \text{ emission rate} = \frac{(\text{CO}_2)}{\text{M}_{\text{CO}_2} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO}_2)}{\text{M}_{\text{CO}_2} \cdot \frac{1}{\text{hr}}} \cdot \frac{(\text{CO}_2)}{\text{M}_{\text{CO}_2} \cdot \frac{1}{\text{hr}}}$$

(d) The times in mode (TMM) shall be as specified below:

Time in mode (minutes)	Class 71, 72 or 73	Class 74, 75 or 76
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15
Testable (est.)	15	15

(e) Meaning of symbols:

(1) HC mass/mode—Total mass of hydrocarbon emissions in pounds emitted during an operational mode as specified in § 87.62 and paragraph (d) of this section.

(2) CO mass/mode—Total mass of carbon monoxide emissions in pounds emitted during an operational mode as specified in § 87.62 and paragraph (d) of this section.

(3) NO_x mass/mode—Total mass of oxides of nitrogen emissions in pounds emitted during an operational mode as specified in § 87.62 and paragraph (d) of this section.

(4) HC emission rate—Pounds/hour of exhaust hydrocarbons emitted in an operational mode.

(5) CO emission rate—Pounds/hour of exhaust carbon monoxide emitted in an operational mode.

(6) NO_x emission rate—Pounds/hour of exhaust oxides of nitrogen emitted in an operational mode.

(7) M_{CO}—Molecular weight of carbon monoxide.

(8) M_{CO₂}—Molecular weight of carbon dioxide.

(9) M_{N₂}—Molecular weight of nitrogen.

(10) M_{H₂}—Atomic weight of hydrogen.

(11) M_C—Atomic weight of carbon.

(12) M_{H₂O}—Atomic weight of water.

(13) For each operating mode: (1) HC—Concentration of hydrocarbons in the exhaust sample in parts per million carbon equivalent, i.e., equivalent propane ± 1.

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§ 87.82 Sampling and analytical system for measuring smoke exhaust emissions.

(a) Schematic drawing. Figure 5 is a schematic drawing of the exhaust smoke sampling and analytical system which shall be used in testing under the regulation in this subpart.

(b) Component description. The following components shall be used in the sampling and analytical system for testing under the regulations in this subpart.

(1) Sample size measurement. A wet ±0.02 cubic foot per minute.

(2) Sample flow rate measurement. Sample flow rate shall be measured with a rotameter with accuracy of no less than ±0.02 cubic foot per minute.

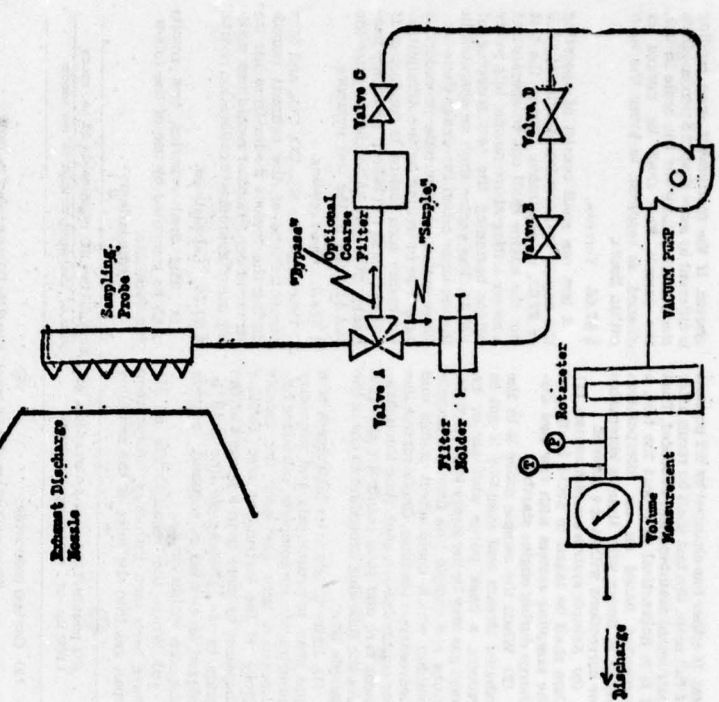


Figure 5 - Sampling System Schematic Diagram

(3) **Filter holder.** The filter holder shall firmly clamp the filter material so that overall system leakage does not exceed that provided in § 87.84(c). The holder internal geometry shall be such that the variation of SN over the sample spot surfaces is not greater than two. Required elements of the filter holder design are given in Figure 6. The filter holder shall be made of corrosion resistant material.

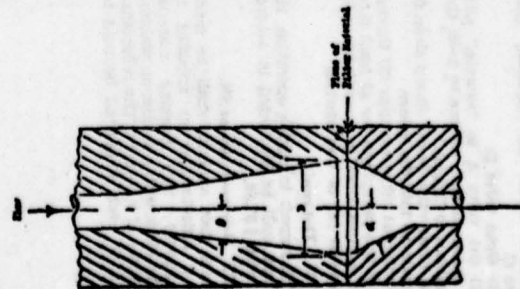


Figure 6—Filter holder assembly

(4) **Sampling probe.** The sample probe and procedure shall be the same as used to show compliance with § 87.84(c).
(5) **Sampling lines.** The sampling lines shall be straight through with no kinks or loops, and no bends having a radius of less than 10 line diameters. Sampling lines inside diameter shall be within 0.18 inch from the probe exit to valve A entrance shall be of minimum length, not greater than 75 feet, with a minimum of fittings

or other breaks. Line material shall be such as to not encourage build-up of either particulate matter or static electric charge, such as stainless steel or copper.

(6) **Valving.** Four valve elements shall be provided. Valve A shall be a quick acting, full-flow, flow diverter with "closed," "sample," and "bypass" positions. Valve A may consist of two valves, provided that they are interlocked so that one of the pair cannot act independently of the other. Valves B and C shall be throttling valves used to establish a system flow rate. Valve D shall be a shut-off valve used in isolating the filter holder. All valves shall be made of corrosion resistant material.

(7) **Vacuum pump.** The vacuum pump shall have a no-flow vacuum capability of at least 22 in. Hg. V., and full-flow capacity of 1 s.c.f.m. minimum.

(8) **Reflectometer.** A reflectometer conforming to ASA standard for diffuse reflection density, number Pb2.17-1958, shall be used. The diameter of the reflectometer light beam on the filter paper shall be no more than one-half of "D," the diameter of the filter spot. The allowable range of "D" is given in Figure 6.
(9) **Filter material.** The filter material shall be Whatman No. 4 filter paper or equivalent approved by the Administrator.

§ 87.83 Information to be recorded.

The following information shall be recorded with respect to each test in addition to that information called for in § 87.85 (a) through (c).

- (a) Sample temperature.
- (b) Sample pressure.
- (c) Actual sample volume at sampling conditions.
- (d) Actual sample flow rate at sampling conditions.
- (e) Leak and cleanliness checks substantiation as required by § 87.84 (b) and (c).

§ 87.84 Calibration and instrument checks.

(a) **Reflectometer calibration.** The reflectometer required by § 87.82(b) shall be calibrated in accordance with manufacturer's specifications.

(b) **System maintenance.** The need for cleaning or replacement shall be determined by conducting the following cleanliness check:

- (1) Pull open valves B, C, and D.

(2) Use the vacuum pump and alternately set valve A to "bypass" and "sample" to purge the entire system with clean air for at least 5 minutes.

(3) Set valve A to "bypass."

(4) Close valve D and clamp clean filter material into the holder. Open valve D.

(5) Set valve A to "sample," reset back to "bypass" after 1 standard cubic foot of air per square inch of filter area has passed through the filter material. If the filter spot exhibits SN greater than 3, the system lines must be cleaned or replaced. The system shall not be used until this cleanliness requirement has been met.

(c) **Leak check.** The following procedure shall be used to leak check the system.

(1) Clamp clean filter material into the holder.

(2) Close valve A, full open valves B, C, and D.

(3) Run the vacuum pump for 5 minutes.

The system shall be satisfactory if no more than 0.20 standard cubic foot passed through the volume meter during 5 minutes. The system shall not be used until this requirement has been met.

§ 87.85 Test procedures.

(a) The engine shall be operated as provided in § 87.82. The leak check and cleanliness check requirements of § 87.84 shall be confirmed before and after each engine test. The test shall be repeated if the requirements of § 87.84 are not confirmed.

(b) **Precautions:** The material being measured is composed of low-micron and/or submicron size agglomerated particles. Precautions should be taken to assure that steady state conditions have been achieved prior to taking a sample. To prevent material accumulation, the system shall not be left in a no-flow condition when exhaust gas is contained.

(c) **Sampling:** Not less than 1 minute shall be allowed to assure that the system is fully charged with a representative gas sample. The sampling flow rate shall be maintained at 0.50±0.02 c.f.m. At least four sample sizes shall be taken within the range of 0.00765 to 0.115 lb. of exhaust gas per square inch of filter. Samples shall be taken both above and below 0.0230 lb. of exhaust gas per square inch of filter.

(d) **Temperature control:** The gas temperature from the sampling probe entrance to the filter material shall be above the dew point temperature. All lines and valves shall be lagged and/or heated as necessary to meet this requirement.

(e) **Preparation for each power setting:** The following shall be done to prepare the system at each power setting:

- (1) Set valve A to "bypass," close valve D.
- (2) Draw exhaust gas for 5 minutes minimum, then use valve C to set flow rate at 0.50±0.02 c.f.m.
- (3) Clamp clean filter material into the holder.
- (4) Open valve D.
- (5) Set valve A to "sample" and use valve B to again set the flow rate to

0.10-0.02 c.f.m. This shall be done quickly before particulate buildup on the filter causes excessive pressure drop. (6) Set valve A to "bypass" and close valve D. (7) Clamp clean filter material into the holder.

(8) Sampling procedure: The procedure for smoke sampling at each power setting shall be as follows:

(1) With valve D closed and valve A set at the "bypass" position, charge the lines with exhaust gas for 1 minute minimum. Reestablish flow rate at 0.10-0.02 c.f.m. as required, using valve C.

(2) Open valve D. (3) Set valve A to "sample," allow the chosen sample volume to pass, then set valve A to "bypass."

(4) Close valve D and clamp clean filter material into the holder.

(5) Repeat subparagraphs (2) through (4) of this paragraph for at least three more sample sizes in accordance with paragraph (c) of this section.

§ 87.86 Test run.

With respect to engine operation, the test run shall be conducted in accordance with § 87.85.

§ 87.87 Determination of SN.

Smoke spot analysis shall be made with a reflectometer as specified in § 87.82(b)(6). The backing material shall be black with a maximum absolute reflectance of 3 percent. The reflectance reading of each spot shall be used to

calculate SN by: $SN = 100(1 - \frac{RS}{RW})$, where RS=absolute reflectance of the sample spot, RW=absolute reflectance of clean filter material.

§ 87.88 Calculations.

(a) Calculation of W. The sample weight (W) shall be calculated by:

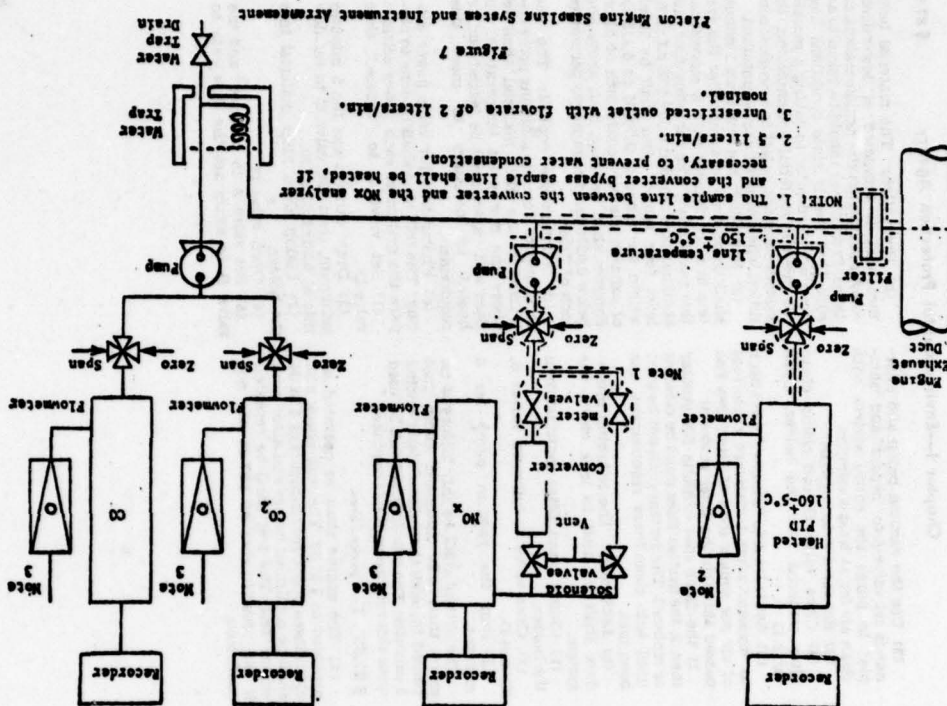
$$W (\text{lb.}) = 1.336 \frac{PV}{T}, \text{ where } P \text{ and } T \text{ are}$$

sample pressure and temperature in units of inches of mercury absolute and degrees Rankine, respectively, measured immediately upstream of the volume meter. V is measured sample volume in cubic feet.

(b) Calculation of W/A. The sample weight in pounds per square inch of filter spot area (W/A) shall be calculated for each sample size taken.

(c) Plotting SN versus W/A. All SN shall be plotted versus W/A on semilog coordinates, with W/A as the logarithmic abscissa. A straight line shall be fitted to these points using the method of least squares. Such a line shall be produced for each power setting specified.

(d) Plotting reporting values of SN versus power setting. Values of SN shall be read from the straight line functions of paragraph (c) of this section for W/A=0.0230 lb/sq. in. These SN are the values to be reported and shall be presented by plotting them as ordinate versus power setting as abscissa on rectangular coordinates.



NOTE 1. The sample line between the converter and the HCN analyzer and the converter sample line shall be heated, if necessary, to prevent water condensation.

2. 5 liters/min.

3. Unrestricted outlet with flowrate of 2 liters/min. nominal.

Figure 7

Diesel Engine Sampling System and Instrument Arrangement

§ 87.89 Compliance with emission standards.

Compliance with each emission standard shall be determined by comparing the plot of SN versus power setting from § 87.88 with the applicable emission standard under this part. The SN at every power setting shall not exceed the standard.

Subpart 1—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft Engines)

§ 87.90 Introduction.

Except as provided under § 87.5, the procedures described in this subpart shall be the test program to determine the conformity of new and in-use aircraft piston engines with the applicable standards set forth in this part.

(a) The test consists of operating the engine at prescribed power settings on an engine dynamometer or test stand. The exhaust gases generated during engine operation are sampled continuously for specific component analysis through the analytical train.

(b) The exhaust emission test is designed to measure hydrocarbon, carbon monoxide, and oxides of nitrogen concentrations and determine mass emissions through calculations during a simulated aircraft landing-takeoff cycle (LTC). The LTC cycle is based on time in mode data during high activity periods at major airports. The test consists of five modes of engine operation: Taxi/idle (out), takeoff, climbout, approach, and taxi/idle (in). The mass emissions for the modes and engine rated power are combined to yield the reported value.

(c) When an engine is tested for exhaust emissions on an engine dynamometer or test stand, the complete engine shall be used with all accessories, which might reasonably be expected to influence emissions to the atmosphere, installed and functioning.

§ 87.91 Gasoline fuel specifications. For exhaust emission testing, fuel meeting the specifications of ASTM D910 latest version for grades 80/87 or 100/130 (as applicable) shall be used. The lead content and octane rating of the fuel shall be in the range recommended by the engine manufacturer.

§ 87.92 Test procedures.

(a) (1) The engine shall be tested in each of the following five engine operating modes which simulate aircraft operation to determine its mass emission rates:

Mode	Power setting (percent of rated power)
Taxi/idle (out)	See subparagraph (2) of this paragraph
Takeoff	100 percent
Climbout	See subparagraph (3) of this paragraph
Approach	40 percent
Taxi/idle (in)	See subparagraph (2) of this paragraph

(2) The taxi/idle operating modes shall be conducted in accordance with the manufacturer's recommended power setting.

(3) The climbout operating mode shall be conducted in accordance with the manufacturer's recommended power setting. Provided, That the power setting shall be between 75 and 100 percent of rated power.

(b) Emission testing shall be conducted on warmed-up engines which have achieved a steady operating temperature.

§ 87.93 Sampling and analytical system for measuring exhaust emissions.

(a) Schematic drawing. Figure 7 is a schematic drawing of the exhaust gas sampling and analytical system which shall be used for testing under the regulations in this subpart. Additional components such as instruments, valves, solenoids, pumps, and switches may be used to provide additional information and coordinate the functions of the component systems.

(b) Water removal devices. No desiccants, dryers, water traps, or related equipment may be used to treat the exhaust sample flowing to the oxides of nitrogen measurement instrumentation. Temperature control shall be provided for NO_x sample lines, hardware and instrument to prevent water condensation.

(c) Component description (exhaust gas sampling system). The following components shall be used in the exhaust gas sampling system for testing under the regulations in this subpart:

(1) Sampling probe. The probe will be made of stainless steel of at least one-fourth inch outside diameter extending across the diameter of the engine exhaust duct.

haust duct. The gas sample will be drawn through a minimum of 5 holes in the sample probe distributed uniformly across the inside diameter of the engine exhaust duct. Where the engine has two or more exhaust pipes, the pipes shall be combined into a common exhaust pipe of sufficient length to provide for good mixing.

(2) Sample transfer. The sample shall be transferred from the probe to the analytical instruments through a stainless steel or Teflon sample line. Sample flow rate from the engine to the instruments shall be such that the transport time from exhaust pipe to instruments is 2 seconds or less.

(d) Component description (exhaust gas analytical system). The analytical system provides for the determination of hydrocarbon concentrations by flame ionization detector analysis, the determination of carbon monoxide and carbon dioxide concentrations by nondispersive infrared analysis and the determination of oxides of nitrogen concentrations by chemiluminescence analysis of exhaust samples. The chemiluminescence method of analysis requires that the nitrogen dioxide present in the sample be converted to nitric oxides before analysis. Other types of analyzers may be used if shown to yield equivalent results and if approved in advance by the Administrator. See Appendix B of this part.

(38 FR 19090, July 17, 1973; 38 FR 34734, Dec. 18, 1973)

§ 87.94 Information to be recorded.

The following information, as applicable, shall be recorded with respect to each test:

- (a) General. (1) Facility performing test.
- (2) Description of test equipment including the probe and sampling and analytical train.
- (3) Instrument operator.
- (4) Test stand operator.
- (5) Fuel identification including H/C ratio and additives, if any.
- (b) Aircraft (in which engine will be tested) description. (1) Manufacturer.
- (2) Model number.
- (3) Serial number.
- (4) Year.
- (c) Engine description. (1) Manufacturer.
- (2) Model number.
- (3) Serial number.
- (4) Displacement.

- (5) Type, manufacturer, and model of carburetor.
- (6) Engine configuration.
- (7) Fuel charger manufacturer and model, if applicable.
- (d) Test data. (1) Test number.
- (2) Date.
- (3) Time.
- (4) Ambient temperature and engine inlet temperature.
- (5) Barometric pressure.
- (6) Relative humidity.
- (7) Sample line temperature.
- (8) Sample line residence time.
- (9) All pertinent instrument information such as tuning, gain, full scale range.
- (10) Recorder charts: Identify zero, span and exhaust gas sample traces.
- (e) Operating mode data. (1) Nominal power setting.
- (2) Actual power setting, horsepower.
- (3) Speed, revolutions per minute.
- (4) Absolute manifold pressure, inches mercury.
- (5) Measured fuel flow, pounds per minute.
- (6) Air flow, pounds per minute and method of determination.
- (7) Pollutant concentration, from records, in percent or parts per million by volume, and parts per million carbon for hydrocarbons.

§ 87.95 Calibration and instrument checks.

Calibration and instrument checks shall be performed in accordance with § 87.86 except that daily calibration and instrument checks shall be performed in accordance with § 87.96.

§ 87.96 Sampling procedures.

(a) HC, CO, CO₂, and NO_x measurements. Allow a minimum of 2 hours warmup for the CO, CO₂, HC and NO_x analyzers. (Power is normally left on infrared and chemiluminescence analyzers; but when not in use, the chamber motors of the infrared analyzers are turned off and the phototube high voltage supply of the chemiluminescence analyzer is placed in the standby position.) The following sequence of operations shall be performed in conjunction with each series of measurements:

- (1) Check the sampling system for any leaks that could dilute the exhaust gas.
- (2) Introduce the zero grade gas at the same flow rates used to analyze the test samples and zero the analyzer. Ob-

tain a stable zero on each amplifier meter and recorder. Recheck after test.

(3) Introduce span gases and set the CO and CO₂ analyzer gains, the HC analyzer sample capillary flow rate and electronic gain control, if provided, and the NO_x analyzer high voltage supply or amplifier gain to match the calibration curves. In order to avoid corrections, span gases should be used at the same flow rates used to analyze the test samples. Span gases should have concentrations equal to approximately 80 percent of each range used. If gain has shifted significantly on the CO or CO₂ analyzer, check tuning. If necessary, check calibration. Re-span at least at end of test but not less than once per hour. Show actual concentrations on chart. Log gain readings.

(4) Check zero; repeat the procedure in subparagraphs (1) and (2) of this paragraph if required.

(5) Check sample line temperature and sample residence time. To check sample residence time:

(i) Introduce HC span gas into sampling system at sample inlet and simultaneously start timer.

(ii) When HC instrument indication is 15 percent of span concentration, stop timer.

(iii) If elapsed time is more than 2.0 seconds, make necessary adjustments.

(iv) Repeat (i) through (iii) with CO, CO₂, and NO instruments and span gases.

(5) Check instrument flow rates and pressures.

(7) The engine shall be operated in each operating mode until emission levels have stabilized as indicated by a constant instrument reading or recorder output. This stabilized reading shall be recorded and used in calculating mass emission rates as called for in § 87.98.

(8) Measure HC, CO, CO₂, and NO_x concentrations of the exhaust sample at the various modes called for in § 87.92.

(9) Recheck zero and span points at the end of the test and also at approximately one hour intervals during the test. If either has changed by ±2 percent of full scale, the test shall be rerun after instrument maintenance: *Provided*, That if it is impractical to repeat the test, a correction based on interpolation linear with time is acceptable for corrections within ±4 percent.

(b) Carbon balance. As a test of representative sample collection, a carbon balance shall be calculated from air and fuel flow data. This balance shall be

within ±5 percent of that calculated from exhaust gas constituents or the test will be invalidated. Fuel flow data shall be derived by measurement during the test for which emissions are to be calculated. Air flow data preferably is from direct measurement but if such measurement is impractical, the data shall be taken from air consumption curves generated for the particular model of engine under test.

(c) Sample system contamination. (1) Care shall be taken to avoid loading of the sampling system with raw fuel discharge during engine starting.

(2) When the sample probe is in the exhaust stream and sampling is not in process, a back purge with air or an inert gas may be necessary to protect the probe and sample line from hydrocarbon buildup.

Check sample line for contamination each time the instrument zero and span points are checked. Use the following procedure to check the sample line:

(i) Immediately after instrument zero and span measurements and necessary adjustments are complete, introduce hydrocarbon zero gas near the sample probe. If the instrument zero reading increases by more than 5 percent of the scale in use the sample line shall be purged or cleaned as required, to bring the zero within limits.

(ii) When the requirements of paragraph (c) (2) (i) of this section have been met, introduce hydrocarbon span gas near the sample probe. If the instrument span reading is different by more than ±5 percent from the correct setting for the scale in use, the sample line shall be purged or cleaned, as required to bring the span within limits. [38 FR 10090, July 17, 1973; 38 FR 94794, Dec. 18, 1973]

§ 87.97 Test run.

A test run shall consist of operating the engine in accordance with § 87.92. The engine shall be operated in the sequence called for under that section without intervening operating points unless an alternate procedure is agreed to in writing by the Administrator before such testing is conducted.

§ 87.98 Chart reading.

Determine the HC, CO, CO₂, and NO_x concentrations of the exhaust sample during the various modes from the instrument deflections or recordings making

ing use of appropriate calibration charts. CO and CO₂ measurements shall be converted to a wet basis by multiplying the recorded concentrations by a conversion factor calculated in accordance with good engineering practices for rich or lean mixtures as appropriate from actual air and fuel flow measurements or from

(a) The final reported test results shall be computed by use of the following formulas:

(1) Hydrocarbon:

$$\text{HC pounds/dry pint per cycle} = \frac{\text{Sum of the HC mass/mode of all of the modes}}{\text{Engine rated power (horsepower)}}$$

(2) Carbon monoxide:

$$\text{CO pounds/dry pint per cycle} = \frac{\text{Sum of the CO mass/mode of all of the modes}}{\text{Engine rated power (horsepower)}}$$

(3) Oxides of nitrogen:

$$\text{NO}_x \text{ pounds/dry pint per cycle} = \frac{\text{Sum of the NO}_x \text{ mass/mode of all of the modes}}{\text{Engine rated power (horsepower)}}$$

(b) The pollutant mass per mode shall be computed by use of the following formulas:

(1) HC mass/mode=HC emission rate \times TIM.

(2) CO mass/mode=CO emission rate \times TIM.

(3) NO_x mass/mode=NO_x emission rate \times TIM.

(c) The emission rates shall be computed by use of the following formulas:

$$\text{HC emission rate} = \frac{\text{HC mass}}{\text{CO mass}} \times \frac{\text{exhaust} \times \text{density}}{\text{CO} \times \text{density}} \times \text{CO emission rate}$$

$$\text{CO emission rate} = \frac{\text{CO mass}}{\text{NO}_x \text{ mass}} \times \frac{\text{exhaust} \times \text{density}}{\text{NO}_x \times \text{density}} \times \text{NO}_x \text{ emission rate}$$

(d) The time-in-mode (TIM) shall be specified in § 87.92 and paragraph (d) of this section.

(1) Test/die (out) 12.0

(2) Test/die (in) 9.0

(3) Approach 6.0

(4) Test/die (in) 4.0

(e) Meaning of symbols:

(1) (i) HC mass/mode=Total mass of hydrocarbons emissions in pounds emitted during an operational mode as specified in § 87.92 and paragraph (d) of this section.

(ii) CO mass/mode=total mass of carbon monoxide emissions in pounds emitted during an operational mode as specified in § 87.92 and paragraph (d) of this section.

(iii) NO_x mass/mode=total mass of oxides of nitrogen emissions in pounds emitted during an operational mode as

average carbon to hydrogen ratio of 1:1.85, in pounds per cubic foot at 68°F. and 760 mm. Hg pressure (0.0339 lb./cu. ft.).

(th) Density CO—Density of carbon monoxide in the exhaust gas in pounds per cubic foot at 68°F. and 760 mm. Hg pressure (0.0726 lb./cu. ft.).

(iii) Density NO_x—Density of oxides of nitrogen in the exhaust gas, assuming they are in the form of nitrogen dioxide in pounds per cubic foot at 68°F. and 760 mm. Hg pressure (0.119 lb./cu. ft.).

(5) HC conc.—Hydrocarbon concentration of the exhaust sample in parts per million carbon equivalent, i.e., equivalent propane x 3.

(ii) CO conc.—Carbon monoxide concentration of the exhaust sample in parts per million by volume.

(iii) NO_x conc.—Oxides of nitrogen concentration of the exhaust sample in parts per million by volume.

(6) TIM—Time in mode as specified in paragraph (d) of this section divided by 60 to yield time in mode in hours.

[38 FR 10600, July 17, 1973, as amended at 38 FR 24794, Dec. 18, 1973]

§ 87.100 Compliance with emission standards.

Compliance with each emission standard shall be determined by comparing the pollutant level in pounds/rated power/cycle as calculated in accordance with § 87.99, with the applicable emission standard under this part. The pollutant level for the cycle shall not exceed the standard.

Subpart J—Temporary Exemption From Aircraft Emission Standards (Fuel Venting and Smoke)

§ 87.101 Application for Temporary Exemption.

(a) The Administrator of the Environmental Protection Agency may grant to any aircraft or aircraft engine temporary exemption from any applicable standard under § 87.11(a) or § 87.31(a), provided that the owner or operator of such aircraft or aircraft engine demonstrates:

(1) All good faith efforts to achieve compliance with such standard.

(2) Ability to comply with such standard, due to circumstances beyond his control, which he will achieve in the shortest time.

(3) A plan which he will achieve in the shortest time.

(b) Applications for temporary exemption from the requirements of § 87.31(a) shall be submitted in duplicate to the Administrator of the Environmental Protection Agency and shall contain the following information:

(1) The name and address of the applicant.

(2) The standard or requirement from which temporary exemption is requested.

(3) The number of aircraft or aircraft engines subject to the requirement for which a temporary exemption is requested.

(4) The efforts made by the applicant to accomplish compliance, including ordering of equipment and scheduling of maintenance work, and the dates of these efforts.

(5) A detailed statement of reasons why the applicant will not be in compliance when the standard or requirement becomes effective.

(6) The name of the equipment supplier and/or the name of the firm retained to perform the maintenance work.

(7) The applicant's proposed timetable for installation of equipment and obtaining necessary approvals for each aircraft or aircraft engine for which temporary exemption is requested, and

(8) The name of the person responsible for accomplishing compliance according to the timetable proposed by the applicant.

(c) Prior to taking action on an application for temporary exemption, the Administrator shall consult with the Secretary of Transportation. A copy of the applicant's request should be submitted by the applicant to the Secretary of Transportation.

(d) The Administrator shall publish in the *Federal Register* the name of the owner or operator to whom a temporary exemption is granted and the period of such exemption.

(e) No state or political subdivision thereof may attempt to enforce a standard respecting fuel venting or engine emissions from an aircraft or engine if such aircraft or engine has been granted an exemption from such standard.

[38 FR 35001, Dec. 21, 1973]

§ 87.102 Thirty-day suspension of fuel venting and smoke standards.

(a) The applicability of the standards of § 87.11(a) and § 87.31(a) to aircraft subject to such standards is suspended until February 1, 1974.

(b) Application for temporary exemption from the standards of § 87.11(a) and § 87.31(a) for aircraft which will not be in compliance by February 1, 1974, must be submitted in accordance with the procedures of § 87.101.

[38 FR 35001, Dec. 21, 1973]

APPENDIX A—INSTRUMENTATION (AIRCRAFT GAS TURBINE ENGINE MEASUREMENTS)

(a) *NDIR instruments.* Nondispersive infrared (NDIR) analyzers shall be used for the continuous monitoring of carbon monoxide and carbon dioxide.

The NDIR instruments operate on the principle of differential energy absorption from parallel beams of infrared energy. The energy is transmitted to a differential detector through parallel cells, one containing a reference gas, and the other, sample gas. The detector, charged with the component to be measured, transduces the optical signal to an electrical signal. The electrical signal thus generated is amplified and continuously recorded. The NDIR analyzer used in accordance with Subpart H of this part shall meet the following specifications:

(1) *Response time (electrical).* 90 percent full scale response in 0.5 second or less. Zero drift—Less than ±1 percent of full scale in 2 hours on most sensitive range. Span drift—Less than ±1 percent of full scale in 2 hours on most sensitive range. Repeatability—±1 percent of full scale on most sensitive range. Noise—Less than 1 percent of full scale on most sensitive range. Cell temperature—Minimum 50° C. maintained within ±3° C.

(2) *Range and accuracy.*

Accuracy excluding interferences

Carbon monoxide:
0 to 100 p.p.m.—±3 percent of full scale
0 to 500 p.p.m.—±1 percent of full scale
0 to 2500 p.p.m.—±1 percent of full scale
Carbon dioxide:
0 to 2 percent—±1 percent of full scale
0 to 8 percent—±1 percent of full scale

(3) All NDIR instruments shall be equipped with cells of suitable length to measure exhaust concentrations within the ranges encountered to the indicated accuracy. Range changes shall be accomplished either by the use of stacked sample cells or changes in the electronic circuitry, or both.

(b) *Total hydrocarbon analyzer.* (1) General description. The measurement of total hydrocarbon is made by an analyzer using a flame ionization detector (FID). With this type detector an ionization current, proportional to the mass rate of hydrocarbon entering a hydrogen flame, is established between two electrodes; the small current is measured by an electrometer amplifier and continuously recorded.

The analyzer shall be fitted with a constant-temperature oven housing the detector and sample-handling components. It shall maintain temperature within ±3° C. of the set point, which shall be within 155° to 165° C.

The detector and sample handling components shall be suitable for continuous operation at temperatures to 200° C.

(2) The FID analyzer used in accordance with Subpart G of this part shall meet the following specifications:

Response time (electrical)—90 percent of full scale in 0.5 seconds or less.

Noise—±1 percent of full scale on most sensitive range.

Repeatability—±1 percent of full scale. Zero drift—Less than ±1 percent of full scale in 2 hours on all ranges.

Span drift—Less than ±1 percent of full scale in 2 hours.

Linearity—Response with propane in air shall be linear with ±2 percent over the range of 0 to 2,000 p.p.m.C.

Accuracy:

0 to 10 p.p.m.C.—±5 percent of full scale with propane calibration gas.
0 to 100 p.p.m.C.—±2 percent of full scale with propane calibration gas.

0 to 1,000 p.p.m.C.—±1 percent of full scale with propane calibration gas.

0 to 2,000 p.p.m.C.—±1 percent of full scale with propane calibration gas.

(3) Total hydrocarbon analyzer shall have an initial alignment as follows:

(1) *Optimization of detector response.* (a) Follow manufacturer's instructions for instrument start-up and basic operating adjustment. Fuel shall be 60 percent hydrogen, 40 percent hydrocarbon containing less than 2 p.p.m.C. hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 2 p.p.m.C.

(b) Set oven temperature at 160° ±5° C. and allow at least one-half hour after oven reaches temperature for the system to equilibrate. The temperature is to be maintained at set point ±3° C.

(c) Introduce a mixture of propane in air at a propane concentration of about 600 p.p.m.C. Vary the fuel flow to burner and determine the peak response. A change in zero may result from a change in fuel flow; therefore, the instrument zero should be checked at each fuel-flow rate. Select an operating flow rate that will give maximum response and least variation in response with minor fuel-flow variations. A typical curve for response versus fuel flow is shown in the following figure.

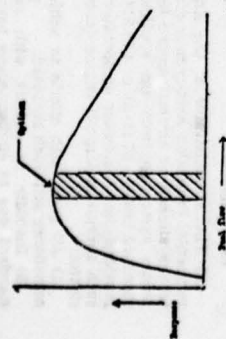


FIGURE 10. FUEL FLOW

(d) To determine the optimum air flow, use fuel flow setting determined above and vary air flow. A typical curve for response versus air flow is shown in the following figure:

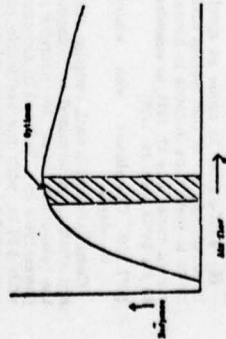


FIGURE 11. AIR FLOW

After the optimum flow settings have been determined these flows are to be measured and recorded for future reference.

(ii) Oxygen effect. Check the response of the detector with varied concentrations of oxygen in the sample following the steps outlined below; this test shall be made with oven temperature at the set point and with gas flow to the detector at optimum conditions, as determined in paragraph (b) (3) (i) of this section.

(a) Introduce nitrogen (N_2) zero gas and zero analyzer; check zero using hydrocarbon-free air; the zero should be the same.

(b) The following blends of propane shall be used to determine the effect of oxygen (O_2) in the sample.

Propane in N_2
Propane in 10% $\pm 0.5\%$ O_2 and balance N_2
Propane in zero grade air (refer to 1.97.06 (c)).

The volume concentration of propane in the mixture reaching the detector should be about 800 p.p.m.C., and the concentration of both the O_2 and hydrocarbon should be

known within ± 1 percent of the absolute value. The zero shall be checked after each mixture is measured. If the zero has changed then the test shall be repeated.

The response to propane in air shall not differ by more than 3 percent from the response to propane in 10% $\pm 0.5\%$ O_2 and balance N_2 . The response to propane in 5 percent O_2 and balance N_2 shall differ by more than 5 percent from the response to propane in nitrogen.

The difference between the response to propane in nitrogen and response to propane in diluent containing 10 percent O_2 shall not exceed 3 percent. If the 2 percent specification cannot be met by changing the sample flow rate or burner parameters, such as air and/or fuel-flow rate, the detector shall be modified or replaced.

(iii) Linearity and relative response. (c) With analyzer optimized in accordance with paragraph (b) (3) (i) of this section, the instrument linearity shall be checked for the ranges covering the range of analysis using propane in air at nominal concentrations of 80, 160, and 320 percent full scale of each range. The deviation of the response from the best-fit straight line shall not exceed 2 percent of the value at any point. If this specification is met, concentration values may be calculated by use of a single calibration factor. If the deviation exceeds 2 percent at any point, concentration values shall be read from a calibration curve prepared during this alignment procedure.

(b) A comparison of response to the different classes of compounds shall be made using (individually) propylene, toluene, n-hexane, and propane, each at 20 to 80 p.p.m.C. concentration in air. If the response to propylene, toluene or n-hexane differs by more than 5 percent from the response to propane, check instrument operating parameters. Reducing sample flow rate improves uniformity of response.

(c) Oxides of nitrogen analytical system. The chemiluminescence method utilizes the principle that nitric oxide (NO) reacts with ozone (O_3) to give nitrogen dioxide (NO_2) and oxygen (O_2). Approximately 10 percent of the NO_2 is electronically excited. The transition of excited NO_2 to the ground state yields a light emission (600-2600 nanometer region) at low pressures. The detectable region of this emission depends on the P2-tube/optical filter being used in the detector. The intensity of this emission is proportional to the mass flow rate of NO into the reactor.

The light emission can be measured utilizing a photomultiplier tube and associated electronics.

(1) The method also utilizes the principle that the thermal decomposition of NO_2 to NO and O_2 is complete at about 600°C. The rate constant for the dissociation of NO_2 at 800°C is approximately 10^4 (liters/mole-second). A 6-foot length of one-eighth inch outside diameter, 0.028 inch wall thick-

ness, stainless steel tubing resistance heated using a low voltage, high current power supply to a temperature of 650°C. Provides sufficient residence time at a sample flow rate of 100 cc. per minute (1.5 cfm) for essentially complete conversion of nitrogen dioxide to nitric oxide. Other converter designs may be used if shown to yield equivalent results.

(3) The method permits continuous monitoring of NO_2 concentrations over a wide range. Response time (2 to 4 sec. is typical) is primarily dependent on the mechanical pumping rate at the operating pressure of the reactor. The following figure is a flow schematic illustrating one configuration of the major components required for the oxides of nitrogen analytical system.

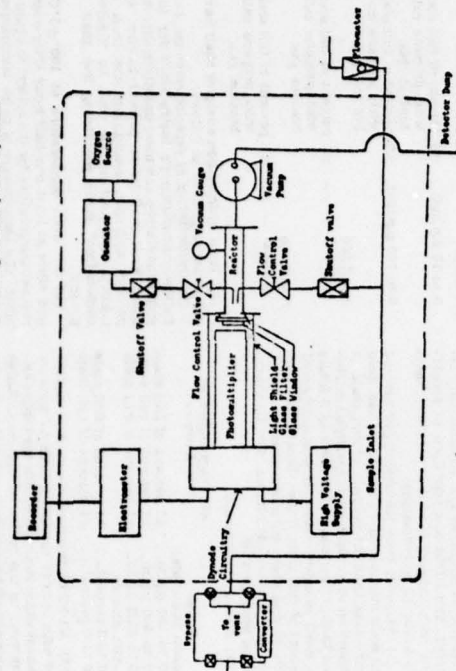


FIGURE 12. OXIDES OF NITROGEN ANALYTICAL SYSTEM

(3) The oxides of nitrogen analyzer used in accordance with Subpart G of this part shall meet the following specifications:

Response time (electrical)—90 percent of full scale in 0.5 seconds or less.

Noise—Less than 1 percent of full scale.

Repeatability— ± 1 percent of full scale.

Zero drift—Less than ± 1 percent of full scale in 2 hours.

Span drift—Less than ± 1 percent of full scale in 2 hours.

Linearity—Linear to within ± 2 percent of full scale on all ranges.

Accuracy— ± 1 percent of full scale on all scales.

(d) The dynamometer test stand and other instruments for measurement of power output from the fuel flow measurement instrumentation in accordance with Subpart G of this part shall be accurate to within ± 2 percent at all power settings.

[38 FR 18090, July 17, 1973; 38 FR 34734, 34735, Dec. 18, 1973]

APPENDIX B—INSTRUMENTATION (AIRCRAFT ENGINE MEASUREMENTS)

(a) The NDIF analyzers used for continuous monitoring of carbon monoxide and car-

bon dioxide in accordance with Subpart I of this part shall meet the following specifications:

(1) Response time (electrical)—90 percent full scale response in 0.5 second or less.

Zero drift—Less than ± 1 percent full scale in 2 hours on most sensitive range.

Span drift—Less than ± 1 percent of full scale in 2 hours on most sensitive range.

Noise—Less than 1 percent of full scale on most sensitive range.

Linearity—Linear to within ± 2 percent of full scale on all ranges.

Accuracy— ± 1 percent of full scale on all scales.

(d) The dynamometer test stand and other instruments for measurement of power output from the fuel flow measurement instrumentation in accordance with Subpart G of this part shall be accurate to within ± 2 percent at all power settings.

[38 FR 18090, July 17, 1973; 38 FR 34734, 34735, Dec. 18, 1973]

APPENDIX B—INSTRUMENTATION (AIRCRAFT ENGINE MEASUREMENTS)

(a) The NDIF analyzers used for continuous monitoring of carbon monoxide and car-

App. B Title 40—Protection of Environment

Zero drift—Less than ± 1 percent of full scale in 2 hours on all ranges.
 Span drift—Less than plus or minus of full scale in 2 hours.
 Linearity—Response with propane in air shall be linear with ± 2 percent over the range of 0 to 20,000 p.p.m.C.

Accuracy:
 0 to 100 p.p.m.C.... ± 8 percent of full scale with propane calibration gas.
 0 to 1,000 p.p.m.C.... ± 3 percent of full scale with propane calibration gas.
 0 to 10,000 p.p.m.C. ± 1 percent of full scale with propane calibration gas.

(c) The oxides of nitrogen analyzer used for measurement of oxides of nitrogen in accordance with Subpart I of this part shall meet the following specifications:

Response time (electrical)—90 percent of full scale in 0.5 second or less.
 Noise—Less than 1 percent of full scale.
 Repeatability— ± 1 percent of full scale.
 Zero drift—Less than ± 1 percent of full scale in 2 hours.
 Span drift—Less than ± 1 percent of full scale in 2 hours.
 Linearity—Linear to within ± 2 percent of full scale on all ranges.
 Accuracy— ± 1 percent of full scale on all scales.

(d) The dynamometer, test stand, and other instruments for measurement of power output and air and fuel flow measurement instrumentation in accordance with Subpart I of this part shall be accurate to within ± 2 percent at all power settings.

PARTS 88-99 [Reserved]

APPENDIX V

REVIEW OF CALIBRATION SPAN GASES

Almost all analytical methods utilize span gases for calibration. For example, a lack of consistency of NO (in N₂) between five samples has been discovered by EPA (230). The five NO in N₂ span gas bottles, all vendor certified at 715 ppm \pm 1% were crosschecked for accuracy on several chemiluminescent and non-dispersive analyzers. These checks showed concentration ranging as high as 1200 ppm and as low as 500 ppm depending upon the bottle used as the span standard.

The Air Pollution Analysis Section of the Analytical Chemistry Division of NBS has been involved in developing standard reference gases. Hughes (231) reported that certain standard reference gases exist, such as mixtures of

CO₂/N₂
C₃H₈/Air
CH₄/Air
O₂/N₂
SO₂ permeation tubes

Other standard reference gases are in preparation, such as

NO/N₂
NO₂ permeation tubes,
and still others are investigated as potential standard reference material, such as
CH₂CH CL/Air
SO₂/N₂
CH₄/Non-methan hydrocarbons/Air

Hughes (1974) states that the preparation of gas mixtures is not particularly difficult and the routine preparation of "standards" is commonplace. However, experience has shown that the accuracy of such standards is often woefully inadequate for the measurements for which the standards are intended. The major reasons for the inadequacy are the uncertainty in assigning an accurate value to the concentration and the uncertainty in the stability of the gas mixture storage and use.

Thus, NBS has been involved in the development of gaseous Standard Reference Materials which required the preparation of a series of primary standards and a deduction of the accuracy of the standards while simultaneously investigating the stability of the primary standards and of the particular gas mixture in the container in which it will eventually be distributed as a Standard Reference Material.

Hughes (1974) has described in some detail the preparation of carbon monoxide and nitric oxide standard reference materials. For example, difficulties of maintaining the original CO concentrations for a period of time is recognized. Some stainless steel cylinders have been found to induce unpredictable and "often disastrous reduction" in CO concentrations.

Similar problems can be encountered with NO. Hughes describes the NBS procedure for producing reference standard material for NO. From his description one can conclude that, concerning the nitric oxide mixtures, it appears that a stable series of standards at concentrations between 50 ppm and 1000 ppm can be provided. A maximum error of between \pm 1 or 2 percent appears to be reasonable and the shelf life and quantity available appears to be adequate.

Gravimetric mixtures can be prepared with an error of about ± 0.2 percent relative. In a sample case the difference between samples approximated the imprecision in the measurement of the sample and the error in the gravimetric samples was considered to be this imprecision.

Hughes then describes the preparation of the test mixture. He states that the major source of error in the composition of mixtures generated by gas blending systems lies in the uncertainty in calibration of the flow measuring devices, i. e., the thermal conductivity type. A description of the calibration procedure is given in the following.

The estimated error in the calculated concentration of a mixture prepared by blending two streams of gas of known composition is about 0.8 percent relative. This is based on the uncertainty in the composition of the stream containing the nitric oxide (0.2 percent) and the errors in calibration of the flowmeters.

Table 3.1 is a summary of results obtained by Hughes using three methods. The calculated value is based on both the measured pressure and the measured weights. The analyzed value was obtained by measurement of the sample using a chemiluminescent analyzer calibrated with mixtures of nitric oxide generated by the dynamic dilution system. Hughes states that there is generally good agreement between all samples with the exception of the value calculated from the pressure data for sample #133. The agreement between the gravimetric result and the analyzer values suggest an error in reading or recording the pressure data for this particular sample.

The value assigned to the primary standards is the value calculated from the gravimetric data. The internal self consistency of the set of gravimetrics shown in Table 2.5 is used to describe the accuracy of these

TABLE 3.1. Summary of Results Obtained by Three Methods for Concentration of Nitric Oxide Standards

Mixture No.	Calculated Concentration Weight	Calculated Concentration Pressure	Observed Concentration
133	960.	(942)	962.
139	951.	951.	948.
140	949.	950.	948.
132	449.	445.	443.
142	451.	449.	447.
143	446.	446.	447.
131	235.	235.	233.
141	227.	229.	225.
145	226.	227.	222.
147	94.4	93.1	94.3
148	94.5	93.5	93.9
149	95.2	94.3	95.1
150	45.4	45.0	45.3
151	46.2	46.0	45.9
152	45.2	45.2	45.3

(All concentrations are in parts per million)

standards and the pressure data and analysis against the dynamic dilution standards is considered confirmatory.

Hughes then states the cylinders in which the Standard Reference Materials were packaged were first treated by soaking with a mixture of nitric oxide in nitrogen at about the concentration with which they were to be finally filled. All cylinders were new and unused and were carefully prepared by drying, evacuating, and flushing with oxygen-free nitrogen. The long term stability is expected to be adequate and will be confirmed by further analyses as described above.

The possibility of an increase in concentration due to desorption of nitric oxide is being investigated by analysis of a number of cylinders from each lot in which the pressure is decreased stepwise from 2000 psi to about 500 psi. Apparently, analyses often do not indicate that any serious desorption occurs but further analyses over a longer period of time will be necessary to confirm this. Several samples in each lot were examined for

other oxides in nitrogen. No evidence of any other oxides within the limits of precision of the measurement were observed. The limits of measurement for this analysis is considered to be about ± 0.2 percent relative. Each lot of fifty-three samples included five samples packaged in aluminum cylinders. It can be shown that the aluminum cylinders offer some advantage.

However, it is not possible to prepare standard reference materials for reactive gases. In that case permeation tubes must be utilized. They consist essentially of a tube of porous material, usually Teflon, containing a liquid such as sulfur dioxide or nitrogen dioxide. The material in the tube permeates through the walls of the tube at a rate determined by the vapor pressure of the substance, and at constant temperature the permeation rate is constant. The devices are used to generate atmospheres containing a known quantity of the substance by placing them at fixed temperatures in a stream of air or other gas flowing at a known rate.

Hughes states that to serve as a satisfactory standard a permeation tube must permeate at a predictable and unchanging rate throughout its useful lifetime. The rates are determined by measurement of the weight loss per unit time at a number of fixed temperatures. The tubes are calibrated by periodic measurement of the weight while maintaining the tube at a constant temperature. Permeation tubes must maintain a predictable rate even after subjection to varying temperature excursions both of use and storage.

Hughes then describes some of the difficulties encountered.

Nitrogen dioxide permeation tubes are not as predictable in use as sulfur dioxide tubes have proven to be, because the rate has been found to decrease significantly with time. This problem appears to lie in drying of the nitrogen dioxide with which the tube is filled and protecting the tube from subsequent exposure to high concentration of water vapor.

Nitrogen dioxide permeation tubes can be calibrated with an accuracy equal to sulfur dioxide tubes of similar output. However, greater caution must

be exercised when weighing tubes because of the hygroscopic nature of the external surface of the permeating area.

As in the case for reference standard materials, commercially available permeation tubes may show large variations. In a recent comparison with NBS certified tubes by McArdie and Hopton (232) discrepancies of up to 55 percent were discovered.

APPENDIX VI

LIST OF COMMERCIALY AVAILABLE POINT SAMPLERS

(From Air Pollution Equipment News, June 1977)

TABLE I: QUICK-REFERENCE SELECTION CHART

	OPERATING PRINCIPLE				sampling method	instrument location	degree of automation	operator skill level	configurations available	power required	monitored air	services offered
	organic gases	inorganic gases	particulates	heavy metals								
AEROCHEM	CM				CT	LB OS	AU		SI		AM CS PS	
AIRFLOW DEVELOPMENT			AS PH		GS CT	OS	MA AU	SK	PA SI TA	AC	CS	
ANACON	CR IR UV	PH		PH	GS CT	LB OS	MA SA AU	US SK	PA SI	AC	AM PS	AP IN FS
ANALYTICAL INSTRUMENTS	CR	CM				LB OS			SI	NE BT	AM CS PS	
ANTEK	CM CR		CM CR		GS CT	LB	AU	SS	PA	AC	AM	AP IN FS TK
APPLIED AUTOMATION	CR	CR		CR	CT				PA		CS PS	
APPLIED ELECTROCHEMISTRY		EC			CT	OS			SI		CS PS	
APPLIED RESEARCH			FL PH	FL PH	CT	LB	MA AU		SI		AM PS	AP
ARCAS	CR IR UV PH	CR IR UV			CT	OS	AU	US SK	PA SI	AC	AM CS PS	AP IN FS TK
BACHARACH	EC			UV	GS CT	OS	MA AU	SS	PA SI	BT AC	AM	AP FS
BAIRD ATOMIC				PH	CT	OS	AU	US	PA	AC	AM	AP IN FS
BASILINE	CR	CR			GS CT	LB CS	MA SA AU	US	PA SI	BT AC	AM CS PS	AP IN FS
BECKMAN	CR IR	CM CR EC WC			CT	LB OS	AU	SK	PA	AC	AM CS PS	AP IN FS TK
BGI		EC			GS CT	LB OS	MA	US SS	SI	BT	AM	IN FS
BIOMARINE	EC	EC			CT	OS	SA AU		PA SI	NE AC	AM	AP
CALIBRATED INSTRUMENTS	IR	EC WC			CT	LB OS	MA AU	US SK	PA SI	NE BT AC	AM CS PS	AP IN FS
CARLE	CR	CR		CR		LB	MA AU		PA SI		AM CS PS	
CEA INSTRUMENTS	IR UV	EC IR UV WC			GS CT	LB OS	MA AU	US SS	SI	BT AC	AM CS PS	AP IN FS TK
CELESCO-BERKELEY		EC			CT	LB OS	MA SA		PA SI	BT AC	CS PS	AP IN FS
CENTURY		CR				LB OS			PA	BT	AM	
CHEMICAL DATA SYSTEMS	CR	CR			GS	LB OS	MA SA AU	SS	PA	BT AC	AM CS PS	AP IN FS TK
CLEVELAND			PH		CT	OS	AU	SS	PA	AC	CS PS	AP FS
CLIMET			PH		GS CT	LB OS	MA SA	SS	PA SI	AC	AM	AP IN FS TK
CONTRAVES-GOERTZ		PH				OS			PA	BT	CS PS	
CONTROL INSTRUMENTS	EP				CT	OS	AU	SS	PA	AC	AM	AP FS
DACO	CR CL PH WC	CR CL PH WC			GS CT	OS	MA	US	PA SI	BT AC	AM CS	AP
DAVIS			PH			OS					CS	
DE-TEC-TRONIC			PH		CT	OS	SA AU	SS	SI	AC	CS PS	AP FS
DELPHI	CR				CT		AU		SI		AM CS PS	
DEVCO ENGINEERING	EC	EC			CT	LB	AU	SS	PA	NE AC	AM	
DICTAPHONE	EC				CT	OS	AU		SI	BT AC	AM	AP FS
DIONEX		CR			GS	LB OS	MA SA	US	PA	AC	AM	AP IN FS

KEY TO ABBREVIATIONS

OPERATING PRINCIPLE

AS ASSAY
CL COLORIMETRIC
CM CHEMILUMINESCENT
CR CHROMATOGRAPHIC
EC ELECTROCHEMICAL
EP ELECTROPHYSICAL
FL FLUORESCENT
IR INFRARED
NC NUCLEONIC
PH PHOTOMETRIC
UV ULTRAVIOLET
WC WET CHEMICAL

SAMPLING METHOD

CT CONTINUOUS
GS GRAB SAMPLING

INSTRUMENT LOCATION

LB LABORATORY
OS ON-SITE

DEGREE OF AUTOMATION

AU AUTOMATED
MA MANUAL
SA SEMI-AUTOMATED

OPERATOR SKILL LEVEL

SK SKILLED
SS SEMI-SKILLED
US UNSKILLED

CONFIGURATIONS AVAILABLE

PA PACKAGED ANALYZERS
SI SENSING INSTRUMENTS
TA TEST APPARATUS

POWER REQUIRED

AC AC
BT BATTERIES
NE NON-ELECTRICAL

MONITORED AIR

AM AMBIENT
CS COMBUSTION EFFLUENT
PS PROCESS EFFLUENT

SERVICES OFFERED

AP APPLICATION/ENGINEERING
FS FIELD SUPPORT
IN INSTALLATION
TK TURN-KEY

	OPERATING PRINCIPLE				sampling method	instrument location	degree of automation	operator skill level	configurations available	power required	monitored air	services offered
	organic gases	inorganic gases	particulates	heavy metals								
DUPONT	CR	PH UV WC	PH UV	AS	GS CT	OS	MA AU	SK	PA SI	BT AC	AM CS PS	
DYNAMATION	EC EP	EC			CT	OS	MA AU	US	SI	BT AC	AM	AP FS TK
DYNATRON			PH		CT	OS	MA SA AU	SS	PA SI	AC	CS PS	AP IN FS
EBI		EC			GS CT	LB OS	MA SA AU	SS	PA SI	BT	AM	AP IN FS
ECA			PH		CT	OS	AU	SS	SI	AC	CS PS	AP
ENMET	EP	EP			CT	OS	AU	US	SI	BT AC	AM CS	AP FS
ENVIRONMENT-ONE	PH		PH		GS CT	LB OS	SA AU	US	SI	BT AC	AM	AP
ENVIRONMENTAL PRODUCTS		EC PH				OS	AU	US	PA SI TA	BT AC	AM CS PS	AP IN FS TK
ENVIRONMENTAL SYSTEMS			IR		CT	OS	AU	US	SI	AC	CS PS	AP IN FS TK
ECCOM	IR	IR			CT	LB OS	AU		PA SI	AC	AM	AP IN FS TK
ERDCO	EP				CT	OS	AU		SI	BT AC	AM PS	FS
ERT						OS	SA AU		SI TA	BT AC	AM CS PS	AP IN FS TK
ESI		EC			GS CT	LB OS	MA SA AU	US	PA SI	NE BT AC	AM CS	AP IN FS TK
EXTECH	CR	CM EC UV			GS CT	LB OS	MA AU	SS	PA	AC	AM CS PS	AP IN FS TK
EXTRANUCLEAR LABS			EC			LB OS	MA SA AU	SS	PA SI	AC	AM CS PS	AP IN FS TK
FINNIGAN	CL CR			CL CR	CT	LB			SI	AC	AM PS	
FISHER SCIENTIFIC	AS	AS CR	CL PH UV WC		GS	LB OS	MA	SS SK	TA	BT AC	AM	AP IN FS
FRONTIER			PH			LB OS	SA	SS	SI TA	AC	PS	AP IN FS TK
GASTECH	UV EG	UV EG			CT	OS	AU	SS	PA SI	BT AC	AM	AP IN FS
GCA			NC		GS CT	OS	MA SA AU	SS	PA SI	BT AC	AM	AP IN FS TK
GENERAL MONITORS	EP	EP			CT	OS	AU	SS	PA SI TA	BT AC	AM	AP FS
GOW MAC	CR	CR			GS CT	LB	MA SA	SS SK	SI	AC	CS	AP FS
GUBELIN	UV CL	CL	PH		CT	OS	AU	SS	SI	AC	AM CS PS	IN FS TK
HNU	PH	PH			CT	LB OS	SA AU	US	PA SI	BT AC	AM PS	AP FS TK
HONEYWELL	CR UV	CR PH			CT	OS	SA AU	SS	PA TA	AC	AM CS PS	AP IN FS TK
HORIBA	IR CR	CM			CT	LB OS	SA AU	SS	PA SI TA	AC	AM CS PS	AP IN FS
HOUSTON ATLAS		CL PH			CT	LB OS	AU	SS	PA SI TA	NE BT AC	AM PS	AP IN FS TK
IKOR			EP		GS CT	OS	MA SA AU	SS	PA	AC	CS PS	AP IN FS
INFRARED	IR	IR			CT	LB OS	MA	US	PA SI	AC	AM CS PS	AP FS
INTERSCAN		EC			CT	OS	SA AU	US	PA TA	BT AC	AM	AP FS
JACOBY-TARBOX			PH		CT	OS	AU		PA SI	AC	AM CS PS	AP FS
KEVEX			CL	CL	GS CT	LB OS	MA SA AU	SS	PA SI	AC		AP IN FS TK
KVB		CM EC FL IR UV			CT	OS	MA SA AU		PA	AC	CS	AP IN FS TK

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AS ASSAY
CL COLORIMETRIC
CM CHEMILUMINESCENT
CR CHROMATOGRAPHIC
EC ELECTROCHEMICAL
EP ELECTROPHYSICAL
FL FLUORESCENT
IR INFRARED
NC NUCLEONIC
PH PHOTOMETRIC
UV ULTRAVIOLET
WC WET CHEMICAL

SAMPLING METHOD

CT CONTINUOUS
GS GRAB SAMPLING

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	OPERATING PRINCIPLE				sampling method	instrument location	degree of automation	operator skill level	configurations available	power required	monitored air	services offered
	organic gases	inorganic gases	particulates	heavy metals								
LA MOTTE	CLWC	CLWC	CLWC	CLWC	GS	OS	MA	US	PATA	NEBT	AM	AP
LEAR SIEGLER	UV	UV	UV		CT	OS	MAAU	SS	PASI	AC	AMCS PS	APIN FSTK
LEEDS AND NORTHRUP	EPCL	EPCLCR				LB OS			SI	AC	AM	
LUFT		WC		WC								
LUMGOR	EC	EC			CT	OS	SA	US	SI	BTAC	AM	
MACLEOD AND STEWART			PH		CT		SA	SS	PA	AC	CS	APIN FSTK
MAST		EC			CT	LB OS	AU	US	PA	BTAC	AM	AP
MATHESON	AS	ASPH		AS	GS CT	LB OS	MAAU	US		NEAC	AMCS	
MC MILLAN		CM			CT	LB OS	SAAU	SS	PATA	BTAC	AMCS PS	APIN FS
MDA	PH	PH			CT	OS	MA SA	SS	PA	BTAC	AM	APIN FSTK
MELOY LABORATORIES	CR	FLPHCM			CT	LB OS	MA SA AU	SS	PASI	BTAC	AMCS PS	APFS
MET ONE			PH		CT	LB OS	AU		SI	BTAC	AM	APIN FSTK
METRONICS				CL	GS	LB OS	MA SA AU	SS	TA	BTAC	AMCS PS	APIN FS
MILTON ROY	CL	CL			CT	OS	SAAU		PASI	BTAC	CS PS	APFS
MOCON	IR	IR			GS CT	LB OS	SA	SS	SITA	BTAC	AM	APIN FS
MONITOR LABS		CM PH			CT	LB OS	AU	SS	PA	AC	AMCS PS	APIN FSTK
MRI			PH		CT	LB OS	MA SA AU	SS	SI	BTAC	AMCS PS	APIN FSTK
MSA	CRIR	CRIR			GS CT	LB OS	MA SA AU	SS	PASI	AC	AMCS PS	APFS
NICOLET	ASIR	ASIR	ASIR		GS CT	LB OS	SAAU	SK	SI	AC	AMCS PS	APIN FSTK
NUCLIDE	CRCL	CRCL		CRCL NC	GS CT	LB	MA SA AU	SS SK	PATA	AC	AM	APIN FS
NUTECH	ASCRECWC	ASWC	ASWC		GS CT	OS	MA SA	SS	PASI TA	BTAC	AMCS PS	AP
PETROLITE				EC	GS	LB	SA	SS	SI	AC	PS	APFS
PGT			FL	FL	CT	LB			PA		AMPS	
PHILIPS		WC			CT		MA SA AU	SS	PA	AC	AM	INFS
PHOTOBELL			CLPHEP		CT	OS	AU	SS	SI	AC	AMCS PS	AP
PHOTOMATION			PH		CT	OS	AU		PA	AC	CS PS	APFS
PRECISION SCIENTIFIC		CL			CT	OS	SAAU	US	PA	NEAC	AM	
RAC	WC	CL EC FL PH UV WC	EC PH UV		GS CT	LB OS	MA SA AU	SS SK	PASI TA	NEBT AC	AMCS PS	APIN FS
RADIAN	CRIR	CM CL FL UV WC	AS PH	AS FL	GS CT	LB OS	MA SA AU	SS SK	PASI	NEBT AC	AM	APIN FSTK
RAECO	CR	CM EC FL IR UV			CT	OS	SA	SS	PASI TA	NEBT AC	AMCS PS	APIN FSTK
RELANCE			PH			OS			PA		CS	
SCOTT	ASIRCL	ASCMIREP			GS CT	LB OS	MA SA AU	SS	PASI TA	AC	AMCS PS	
SGA		CM			CT				PA		AMCS PS	
SNAP-ON	IR	IR				OS			PA		CS	
TAYLOR	EP	EP			GS CT	LB OS	AU		PA	BTAC	CS PS	APFS
TECH ECOLOGY			PH			LB OS					AM	
TECHNICON	CLWC	CLWC			GS	LB OS	AU	SS	PA	AC	AM	APIN FS
TELEDYNE ANALYTICAL	CL	CL			CT	LB OS	AU		PASI	AC	AMCS	
THERMCO		EP			CT	OS	AU	SS	PA	AC	AMCS	APIN FS
THERMO-ELECTRON		CM FL			CT	LB OS	MA SA AU	SS	PASI	AC	AMCS PS	APIN FSTK
THETA		EC			GS CT	LB OS	MA	SS	PASI	BTAC	AMCS PS	APIN FSTK

TRACOR		CR			GS CT	LB OS	MA AU	SS			CS	AP IN FSTK
TUDOR	CR CL WC	CR CL WC	CR CL WC		GS CT	LB OS	MA	SS SK	PA TA	NE		
UNITED TECHNICAL	CR	CR	EC FL PH		GS	LB OS	MA SA AU	SS	PA SI TA	BT AC	AM CS PS	AP IN FSTK
VARIAN	CR	CR		PH	GS	LB	AU	SS	PA	AC	AM CS PS	
WAGER			PH		CT	OS	SA	SS	SI	BT AC	CS PS	AP PS
WARD	CL				GS CT	LB OS		US	PA	NE	AM	
WESTERN PRECIPITATION		EC	PH		GS CT	OS	MA SA AU	SS SK	PA SI TA	BT AC	AM CS PS	AP IN FS
WESTERN RESEARCH & DEVELOPMENT	CR	AS CM CR CL IR UV WC	AS	WC	GS CT	LB OS	MA AU	SS SK	PA SI TA	AC	AM CS PS	AP IN FSTK
WESTINGHOUSE		EP				LB OS	AU		SI	AC	CS PS	
WHITTAKER		EC	EC		CT	OS			PA SI	AC	AM	
XONICS	CR	PH CM			CT	LB OS	SA AU	SS	PA	AC	AM	AP IN FSTK

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APPENDIX VII

DERIVATION OF SIGNAL-TO-NOISE RATIO
EQUATIONS AND ERROR ANALYSIS

(VII-1)

$$\frac{dx}{dy} = \frac{1}{\frac{dy}{dx}}$$

where dx is the error for noise of x . When the quantity x depends on the variables y_1, y_2, \dots, y_n , the error dx is determined on the principle of superposition of errors, which is given by the total error differential, viz.,

$$dx = \frac{\partial x}{\partial y_1} dy_1 + \frac{\partial x}{\partial y_2} dy_2 + \dots + \frac{\partial x}{\partial y_n} dy_n$$

$$\frac{dx}{dy} = \frac{1}{\frac{dy}{dx}}$$

where dy_i are the errors for each variable y_i . The most probable value of dx is the square root of the sum of the squares of the individual errors.

Thus,

APPENDIX VII

DERIVATION OF SIGNAL-TO-NOISE RATIO
EQUATIONS AND ERROR ANALYSIS

In this appendix we derive a generalized set of SNR expression for remote monitors, discuss some of the fundamentals in statistical error analysis and consider questions in instrument accuracy.

Derivation of Signal-to-Noise Equations

The accuracy with which a physical quantity x can be observed experimentally is given by

$$\text{SNR} = \frac{x}{dx} \quad (\text{VII-1})$$

where dx is the error (or noise) of x . When the quantity x depends on the variables y_i , the total error is determined on the principle of superposition of errors⁽¹⁶²⁾, which is given by the total error differential, viz.,

$$\begin{aligned} dx &= \frac{\delta x}{\delta y_1} dy_1 + \frac{\delta x}{\delta y_2} dy_2 + \dots \\ &= \sum_i \frac{\delta x}{\delta y_i} dy_i \end{aligned}$$

where dy_i are the errors for each variable y_i . The most probable value of dx is the square root of the sum of the squares of the individual errors. Thus,

$$(dx)_{\text{rms}} = \sqrt{\left(\frac{\delta x}{\delta y_1} dy_1\right)^2 + \left(\frac{\delta x}{\delta y_2} dy_2\right)^2 + \dots}$$

and

$$\begin{aligned} \text{SNR} = \frac{x}{(dx)_{\text{rms}}} &= \frac{1}{\sqrt{\left(\frac{\delta x}{\delta y_1} \frac{dy_1}{x}\right)^2 + \left(\frac{\delta x}{\delta y_2} \frac{dy_2}{x}\right)^2 + \dots}} \\ &= \frac{1}{\sqrt{\frac{1}{(\text{SNR})_{y_1}^2} + \frac{1}{(\text{SNR})_{y_2}^2} + \dots}} \end{aligned} \quad (\text{VII-2})$$

The limiting sensitivity of a system that measures the quantity x is given by Eq. (VII-2) and setting SNR to unit, viz.,

$$(x)_{\text{SNR}=1} = (dx)_{\text{rms}}$$

where $(x)_{\text{SNR}=1}$ is called the "noise-equivalent-quantity x ". (Typical examples are noise-equivalent-radiance [NEN], noise-equivalent-temperature [NET], noise-equivalent-concentration [NEC], noise-equivalent-power [NEP], etc.)

We will now give several examples in which the quantity x is substituted by different physical parameters.

Example 1. The physical parameter to be measured is the radiant power P from a source. Assuming there are no variables influencing P , then $x = P$ and $dx = dP$. The noise dP is generally composed of three components: The shot noise due to the arrival of signal photons, the background noise and the detector noise; i. e., $\left(\frac{h\nu}{\eta t_g} P\right)^{1/2}$, $\left(\frac{h\nu}{\eta t_g} P_B\right)^{1/2}$, and NEP, respectively. The square of the noise is then given by^{(111)g}

$$(dP)^2 = \left(\frac{h\nu}{\eta t_g} P\right) + \left(\frac{h\nu}{\eta t_g} P_B\right) + (NEP)^2 \quad (\text{VII-3})$$

where h is the Planck constant, ν is the frequency at which the radiant power P is observed, η is the quantum efficiency of the detection system and t_g is either the gate time, integration time or pulse width, P_B is the radiant power of the background and NEP is the noise-equivalent-power due to the detector. The magnitude, and thus the significance, of the noise components is different in the UV and IR portions of the spectrum because of the different types of detectors used. In the UV, where usually photomultipliers are employed, the first component is always significant and the second one is significant only for long integration times. The third term (noise due to the dark current of the PM tube) can be neglected. In the IR, where photoconductors are used, the first term may always be neglected and the second one may or may not be important. The third term is always important, unless of course the background term is dominating.

Thus, for example 1, the appropriate expression for the signal-to-noise ratio is

$$\text{SNR} = \frac{P}{(dP)_{\text{rms}}} = \frac{P}{\left[(P + P_B) \frac{h\nu}{\eta t_g} + (NEP)^2\right]^{1/2}} \quad (\text{VII-4})$$

If one can neglect the background noise, the SNR in the UV becomes

$$\text{SNR} = \sqrt{P \eta t_g / h\nu} \quad (\text{VII-5})$$

and in the IR becomes

$$\text{SNR} = \frac{P}{\text{NEP}}$$

Example 2. The physical parameter x is to be determined by the sum or difference of two measured signals. Thus,

$$x = P_1 \pm P_2$$

$$dx = dP_1 \pm dP_2$$

The most probable error is given by

$$(dx)^2 = (dP_1)^2 + (dP_2)^2$$

With the reasonable assumption that $dP_1 \approx dP_2$, the SNR becomes

$$\text{SNR} = \frac{P_1 \pm P_2}{\sqrt{2} \, dP} \quad (\text{VII-6})$$

Example 3. The physical parameter x is to be determined by the ratio of two measured signals:

$$x = P_1/P_2$$

$$dx = dP_1/P_2 - P_1 dP_2/P_2^2$$

The most probable error is given by

$$(dx)^2 = \left(\frac{P_2 dP_1}{P_2^2} \right)^2 + \left(\frac{P_1 dP_2}{P_2^2} \right)^2$$

For the case of $dP_1 \approx dP_2$, the SNR becomes

$$\text{SNR} = \frac{P_1 P_2}{dP \sqrt{P_1^2 + P_2^2}}$$

Example 4. The physical parameter x is to be determined by the \ln of the ratio of two signals, as in a transmission experiment. Thus

$$e^x = P_1/P_2$$

$$x = \ln P_1 - \ln P_2$$

$$dx = dP_1/P_1 - dP_2/P_2$$

The most probable error is given by

$$(dx)^2 = (dP_1/P_1)^2 + (dP_2/P_2)^2$$

Again, in case of $dP_1 \approx dP_2$, the SNR becomes

$$\text{SNR} = \frac{\ln P_1/P_2}{dP \sqrt{(1/P_1)^2 + (1/P_2)^2}} \quad (\text{VII-8})$$

For small x (i. e., almost transparent atmosphere), $P_1 \approx P_2$. Thus,

$$\ln P_1/P_2 \approx P_1/P_2 - 1$$

and

$$\text{SNR} \approx \frac{P_1(P_1 - P_2)}{dP \sqrt{P_1^2 + P_2^2}} \approx \frac{P_1 - P_2}{dP \sqrt{2}} \quad (\text{VII-9})$$

Equation (VII-8) may be expanded for the application of a pulsed system, where the signals are composed of the difference of two signals observed at two different times. Thus,

$$\text{SNR} = \frac{\ln P_1 P_2' / P_2 P_1'}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2 + (1/P_2)^2 + (1/P_2')^2}} \quad (\text{VII-10})$$

Accuracy Considerations

Dieck and Elwood⁽²⁴⁷⁾ have formalized their approach to accuracy analysis which they first reported on in 1974⁽²³⁸⁾. Their analysis is based upon the statistical approach outlined by Natrella⁽²⁴⁸⁾. We will follow here their analysis.

There are two basic types of errors: Bias (or systematic) errors and precision errors. Bias error is a measure of the deviation of the average from the true value x_t . Precision error is a measure of the instrument repeatability, i. e., the scatter about the biased average. The two errors are described mathematically by

$$\text{Bias error } b = \bar{x} - x_t$$

$$\text{Precision error } \sigma = \sqrt{\sum_i (x_i - \bar{x})^2 / (n-1)}$$

where n is the number of measurements and \bar{x} is the mean value of x . A graphical representation is given in Figure VII-1.

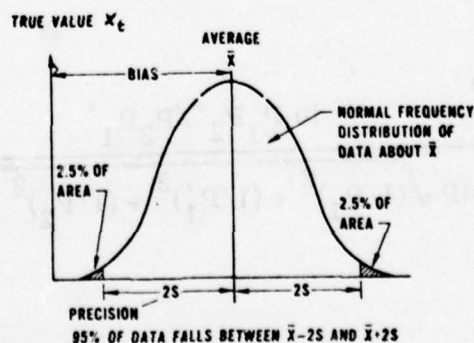


Figure VII-1. Effect of Bias and Precision Errors.

Therefore, the precision error is given by the mean deviation of the normal distribution of data about \bar{x} . The normal frequency distribution or Gauss distribution is given by⁽¹⁶²⁾

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\bar{x})^2/2\sigma^2}$$

The area under this curve, extending from $-\infty$ to $+\infty$, is normalized so that the probability that an observation will lie between two values x_1 and x_2 is represented by the area under the curve between x_1 and x_2 , i. e.,

$$\frac{1}{\sigma\sqrt{2\pi}} \int_{x_1}^{x_2} e^{-(x-\bar{x})^2/2\sigma^2} dx$$

writing $\xi = (x - \bar{x})/\sigma$

$$\xi_1 = (x_1 - \bar{x})/\sigma$$

$$\xi_2 = (x_2 - \bar{x})/\sigma$$

the integral becomes

$$\frac{1}{\sqrt{2\pi}} \int_{\xi_1}^{\xi_2} e^{-1/2\xi^2} d\xi$$

This integral can be expressed as the difference of two integrals of the type

$$\frac{1}{\sqrt{2\pi}} \int_0^t e^{-1/2\xi} d\xi$$

This integral has been evaluated for different values of t . It should be noted that the function

$$\frac{1}{\sqrt{\pi}} \int_{-t}^t e^{-\xi^2} d\xi = \frac{2}{\sqrt{\pi}} \int_0^t e^{-\xi^2} d\xi = \text{erf}(t)$$

is known as the error function. Thus,

$$\frac{1}{\sqrt{2\pi}} \int_0^t e^{-1/2\xi^2} d\xi = \frac{1}{\sqrt{\pi}} \int_0^{t\sqrt{2}} e^{-\xi^2} d\xi = \frac{1}{2} \text{erf}(t\sqrt{2})$$

Representative values of $\text{erf}(t\sqrt{2})$ are given below:

t	$\text{erf}(t\sqrt{2})$
0	0
0.6745	0.5
1.0	0.6827
2.0	0.9543
3.0	0.9973
"	1.0

Therefore, one can see that in a normal distribution the probability that an observation lies within $\pm 2\sigma$ of \bar{x} is 0.9543. Of particular interest is the value $\bar{x} \pm 1.96\sigma$ for which $\text{erf}(t/\sqrt{2}) = .95$, the so-called 95% confidence interval.

Dieck and Elwood show as an example the propagation of bias and precision errors through several levels of a calibration hierarchy (see Figure VII-2). The top level of uncertainty is the National Bureau of Standards,

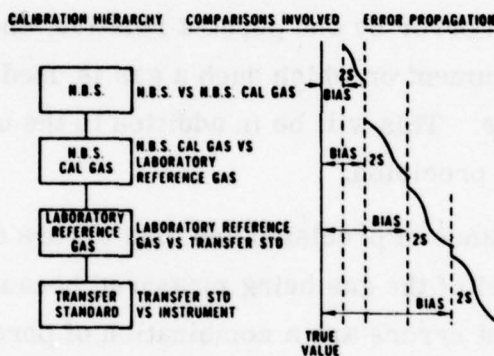


Figure VII-2. Propagation of Error in a Calibration Hierarchy.

the second level, the National Bureau of Standards' supplied laboratory reference gas. The third level is the transfer standard calibration gas which, after comparison to the laboratory reference, is used to calibrate the instruments on the fourth level (i. e., the measuring instruments used). The precision of the fourth level is referred to as the calibration-to-calibration precision. Where NBS standard reference materials are not available, the problem of ascertaining the accuracy of the first level becomes even more complex.

Fundamental to the assessment of instrument accuracies is the proper choice of units: should accuracy be described as percent of point (a relative basis) or percent of full scale (an absolute basis). Data with normally distributed errors permit the use of terms such as precision and variance in a way in which they are generally understood and clearly defined. Dieck and Elwood suggest the use of percent of full scale units as the best units for the instruments' precision errors.

Bias errors, however, should be expressed as relative errors because they are largely a result of calibration gas uncertainty. If a calibration gas is in error by one percent relative, the entire range of the measuring instrument on which such a gas is used for calibration will be off by 1% relative. This will be in addition to the uncertainty contributed by the instrument's precision.

The significance of precision and bias errors depends in large measure on the level of the gas being measured because the gas concentration measurement errors are a combination of percent of full scale and percent of point error. The instrument errors are percent of full scale, one value to be utilized over an entire instrument range. They usually dominate the errors on the lower half of an instrument range. Calibration gas errors are percent of point and, therefore, depend on the level of the gas concentrations being measured. Calibration gas bias errors usually dominate on the upper half of an instrument's range.

By evaluating the precision with which an instrument repeats when reading the calibration gas, an estimate may be had of the instrument's precision when reading a test point. Calibration precision is utilized because the calibration gas concentration is assumed invariant (for the duration of a test) thus placing all variations as instrument caused.

Dieck and Elwood found a considerable variability in instrument precision from day to day and range to range. The existence of the variability, however, requires the evaluation of the instrument precision on the day when field tests are to be undertaken. Dieck and Elwood state that daily precision error estimates must be combined with calibration gas uncertainties for the proper expression of emission measurement accuracies. In Table VII-1 they compare the Environmental Protection Agency's required emission instrument precisions with those typically obtained in use. For most cases for which there is some comparison, typical in use, in day precision is worse than that required by the EPA.

TABLE VII-1. Comparison of EPA Required Instrument Precisions—Those Typically Obtained In-Use in One Day.

Constituent	Range	In-use precision	EPA required precision
CO ₂	0-2%	0.02%	0.02%
	0-5%	0.09%	0.05%
CO	0-100 ppm	3.0 ppm	1.0 ppm
	0-500 ppm		5.0 ppm
	0-1000 ppm	19.6 ppm	10.0 ppm
	0-2500 ppm		25.0 ppm
HC	0-10 ppm C		0.1 ppm
	0-100 ppm C	4.0 ppm	1.0 ppm
	0-1000 ppm C	22.0 ppm	10.0 ppm
	0-2000 ppm C	20.0 ppm	20.0 ppm
NO _x	0-200 ppm NO _x		2.0 ppm
	0-500 ppm NO _x		5.0 ppm
NO	0-200 ppm NO	5.0 ppm	2.0 ppm
	0-500 ppm NO		5.0 ppm
NO ₂	0-200 ppm NO	5.0 ppm	2.0 ppm
	0-500 ppm NO		5.0 ppm

The authors state further that "EPA parameters such as accuracy and precision were not well defined in their regulations; it is assumed here that the precision required is 2σ over the 95% confidence interval. This precision comparison underscores the need for continued, current evaluation of emission instrument performance and the need to recognize the possible difference between typical in-use precision and that required by the EPA. "

APPENDIX VIII

METEOROLOGICAL INSTRUMENTS FOR USE
IN THE CALIBRATION TEST RANGE

APPENDIX VIII

Meteorological Instruments for Use in the Calibration Test Range

relatively short moment arm. In addition, friction has been reduced by utilizing miniature ball bearings and special type transmitters. The cups are generally 5 cm. in diameter and have a moment arm of about 7 cm. By using six staggered cups, a greater surface area is exposed to the wind. This factor decreases the starting threshold from .75 mph (.35 m/s) for the standard 3-cup anemometer to .4 - .5 mph (.2 - .25 m/s). This design also produces a more uniform torque around the entire shaft revolution.

The second most commonly used wind speed measuring system is one that has a propeller on the end of a horizontal shaft that is oriented into the wind by a vane on the opposite end of the shaft. The propeller is usually helicoidal in design, with the rate of rotation of the propeller being linearly proportional to the wind speed. The more sensitive propeller anemometers utilize lightweight aluminum or plastic as blade material, and generally employ either 2 or 4 blades. The 2-bladed propellers have starting speeds of about .4 - .7 mph (.2 - .35 m/s), while the 4-bladed propellers have a threshold of about .3 - .5 mph (.15 - .25 m/s).

In order to convert the rotation to an energy form that is transmittable, four types of transducers are in use; the D. C. generator, the A. C. generator, a light chopper and mechanical contact.

Small, permanent field D. C. generators are used that have an output which is linearly proportional to the rate of turning of the cup or propeller and, hence, is linearly proportional to the wind speed. The output from this transducer can be recorded directly on any D. C. galvanometer recorder. The main disadvantage of D. C. generators is the relatively high starting or threshold speeds. The brush and bearing friction combine to produce a lower limit to the threshold speed of about 1 mph (.5 m/s) on the most sensitive systems. The brushes on these generators usually need servicing only about once a year under continuous use.

In order to describe fully the atmospheric environment in a calibration test range for remote sensors, the wind velocity (direction and speed), the humidity, temperature, precipitation, and solar radiation must be known accurately. A description of available instrumentation techniques is given in the following (Adopted from Ref. 233). Additional information may be found in Refs. 234-238.

Wind Speed Sensor

Rotational anemometers (vertical and horizontal) are the most common type in use today mainly because they are the only types that satisfy all of the following desirable operational features: (1) Essentially linear relationship between the sensor output and the wind speed; (2) Calibration is unaffected by changes in the temperature, pressure or humidity of the atmosphere; (3) Able to measure a wind range of wind speeds (<2 to 200 mph); (4) Long term calibration stability. The calibration often is unchanged after 10 years continuous operation; (5) Output of the sensor is easily adapted to remote indication; (6) Recording of the wind speed data is easily adaptable to either analog or digital form; (7) Generally require extremely little maintenance. Light weight vertical shaft anemometers were developed for air pollution meteorology. To provide accuracy at low speeds and sufficient sensitivity, these small 3-cup anemometers are lightweight in construction (plastic or very thin aluminum) and employ a

In an attempt to lower the threshold speed by eliminating brush friction, A. C. generators are used instead of D. C. generators. A. C. generators reduce the friction considerably and eliminate brush and commutator maintenance. A. C. generators are available with either two, four, six, or eight-pole permanent magnet rotors. The larger the number of poles, the more pulses are available per shaft revolution, producing a smoother record.

The largest disadvantage of the A. C. generator is associated with the number of pulses per shaft revolution. These pulses must be rectified for recording. Low wind speeds generate a low frequency of A. C. pulses and normal rectifiers do not function properly with a low frequency input and spurious oscillations may be produced. Therefore, to obtain wind speeds below about 2 m/sec (4 mph) some sort of electronic correction is needed. This disadvantage defeats the purpose of reducing the friction and has therefore resulted in a minimal use of this type of transducer.

Further reduction in friction with accompanying lower threshold speed and quicker response can be accomplished with the use of an interrupted light beam (light chopper) transducer. This transducer employs either a slotted shaft, a slotted disc, a light source and a photocell, or photo-diode. The cup or propeller rotates the slotted shaft or disc and a pulse is created each time a slot allows light from the source on one side of the shaft or disc to fall on the photocell on the other side of the shaft or disc. The larger the number of slots in the shaft or disc, the smoother will be the output, especially at low wind speeds. The output from the transducer is handled in the same manner as the output from the A. C. generator. The large number of slots (about 100) prevent spurious oscillations in the output at low wind speeds.

All of the measuring transducers mentioned so far produce an analog signal. There are circumstances where the desired output might be total miles of wind passage instead of a time plot of wind speed. Under these circumstances, a mechanical-contact transducer is used. In this type of

transducer, the anemometer shaft is connected through one or more gears to a cam or similar device that opens or closes a contact after the passage of a pre-determined amount of air. This contact closure can operate a readout device such as an event marker pen on a recorder. Recorders can be furnished with circuitry to provide a pen actuation for each 10, 100, or 1000 contact closures in the transducer. If the average wind speed is desired instead of length of wind passage, the number of contact closures are determined for a given time increment and, knowing the miles or meters of wind passage for each contact closure, the average wind speed over the given time increment is easily determined.

There are a number of other devices such as pressure anemometers, hot wire and sonic anemometers. But they all have disadvantages which have prohibited so far their use in operational type situations.

Wind Direction Sensors

These are made up of vanes of different configurations. The flat plate vane can take on a number of different shapes and be made out of a number of different materials. As with wind speed sensors, the material used in constructing the wind vane will generally determine the proper use of the vane. Vanes made out of heavy gauge metal or plastic can be used only for obtaining average wind direction. The large mass creates a high moment of inertia which will give, under certain conditions, a much higher indication of wind fluctuations than actually exists. The light-weight sensitive vanes have tails made out of thin gauge aluminum or plastic or molded expanded polystyrene. The counterweights are also close to the center of rotation. This design creates a highly sensitive vane that can be suitably used for turbulence measurements.

In the splayed vane, two flat plates are joined at a small angle (usually about 15°) at one end of the horizontal shaft. This design came about through experimentation that showed that the splayed vane followed small changes in wind direction better than the flat plate. However, the increased mass incurred by two flat plates makes this type of vane unsuitable for anything but the measurement of average wind direction. The splayed vane has, mainly because of its durability and reliability, found widespread use in its role as the main wind direction sensor for the National Weather Service. Therefore, it should be noted that wind direction data obtained from a National Weather Service should be used only as an indication of average wind direction.

The aerodynamic shaped vane has an airfoil cross section. This type of vane has been shown to produce up to 15% more torque for certain ranges of attack angles than a flat plate vane of similar physical dimensions. This type of design, as with the splayed vane, incorporates more mass than the flat plate vane and therefore produces a higher moment of inertia, yielding a poor dynamic performance.

The bidirectional vanes are designed to rotate around a vertical axis to measure the azimuth angle of the wind, as does a conventional wind vane. It also can move in the vertical to measure the elevation angle of the wind. Because the vertical motions of the atmosphere are frequently of a different character than the horizontal motions (anisotropic turbulence), measurement of both the horizontal and vertical motions are desirable. This is particularly true under stable conditions when the vertical motion is almost absent, but horizontal changes in wind direction may be appreciable. Micropotentiometers are usually used to produce an analog record of both angles. The total wind speed can be measured by replacing the counterweight with a propeller anemometer.

The measurement of wind direction consists of converting the angular position of the wind vane to an energy form that can be transmitted easily. The sensitive wind direction systems usually employ a potentiometer system, or a synchro-motor system.

The most common and inexpensive way of converting the angular position of the vane to an electrical signal is through the use of a potentiometer system. In this system the shaft of the vane is attached to the wiper arm of the potentiometer. The swinging vane therefore produces a continuously varying voltage that can be recorded on a recording voltmeter or dial indicator. With proper calibration, the recorded voltage gives a direct reading of the angular position of the vane. The biggest drawback to this system is the unavoidable discontinuity in the potentiometer. If the wind direction is oscillating about a direction corresponding to this gap, the voltage output will oscillate between the maximum and minimum value. There are some types of recorder pen movements available that circumvent this problem. The use of micro-potentiometers produces the lowest moment of inertia of any of the direction transducers available today. This fact has led to their widespread use in the sensitive wind vanes that are noted for their good dynamic performance.

This transducer system consists of two synchronous motors wired so that any movement by the shaft of the transmitter will be duplicated by the shaft of the receiver motor, usually to an accuracy of about 2° , provided the lead resistance is kept to a maximum of 20 ohms. The vane shaft is coupled to the shaft of the transmitter motor and the shaft of the receiver motor is coupled to a recorder pen or some other read-out indicator. Therefore, any vane movement is duplicated by a movement of the dial needle, recorder pen, etc., and with proper calibration and alignment, a direct indication of wind direction is obtained. There is no discontinuity in the movement as with the potentiometer. The only disadvantage of this

transducer system is the relatively large moment of inertia of the motor assembly. This produces a poorer dynamic performance than the micropotentiometer system and limits their use to the more rugged vane types.

Temperature Lapse Rate

The vertical structure of temperature gives an indication of the stability and turbulence of the atmosphere. One method of estimating the vertical structure of temperature is by measuring the difference in temperature between sensors mounted at different heights. This, of course, gives an average condition between any two particular sensors. Because of the pronounced influence of the earth's surface on the atmosphere's temperature, it is desirable to measure temperature difference at closer intervals near the ground than at higher levels. Resistance thermometers of copper or nickel may be used for temperature difference systems. Thermocouples of copper-constantan or iron-constantan also make reliable sensors. Resistance thermometers and thermocouples do not have to be frequently calibrated. Thermistors are more variable from unit to unit and they require recalibration more frequently than the other two types of sensors. Rapid response is usually not desired in measuring temperature differences. Rather, averages on the order of 5 minutes are desired. If the sensors are 1/2 to 5/8 inch in diameter, they will respond slowly enough to give an average temperature. Precautions must be exercised in the shielding and ventilating of temperature sensors. (234-237)

The method of radiosonde (radio-soundings) observations is used routinely for temperature, pressure and humidity soundings of the upper air. A free balloon carries the sensors and a radio transmitter aloft. Cycling from sensor to sensor is by means of an aneroid barometer and consequently is a function of pressure. Observations are normally made twice daily at 0000 GCT and 1200 GCT at approximately 70 stations in the contiguous U. S. The ascent rate of the balloon is about 1000 ft/minute.

Generally only four to six temperature readings are recorded within the lower 3000 feet so the vertical temperature information is not too detailed. It is still of considerable use when more detailed information is not available.

T-Sonde consists of a temperature sensor and radio transmitter which is carried aloft by a free rising balloon. The main difference between this system and the radiosonde system is that only temperature is measured. Ten to twelve measurements are taken within the lower 3000 feet of the atmosphere, thus giving more detailed structure of temperature with height.

Using a captive balloon system to make vertical temperature measurements has the advantages of complete recovery of all components of the system, and as detailed a temperature sounding as is desired may be made by control of the level of the sensor. A balloon having fins is much easier to control and gives greater lift in slight winds than a spherical balloon. Most kite balloons can be used in winds less than 15 knots. For air pollution meteorology purposes, the light wind periods are of greatest interest. Because of hazards to aircraft, prior permission from the FAA is required for flights exceeding 500 feet above ground. For additional precautions when using captive balloons, see references 234-237.

Several methods of relaying the observations to the ground have been used. Using a wire, a resistance thermometer is carried aloft by a kite balloon whose mooring cable contains wires connecting the sensor with a wheastone bridge on the ground which is used to measure the resistance. Another system uses a modified radiosonde transmitter to measure temperature and humidity. The signal is transmitted to the ground receiver and recording equipment by the same method used in the radiosonde. Cycling from one sensor to another by a battery driven timing device. The temperature sensor is shielded from the sun by the styrofoam plastic and is aspirated by a small motor driven fan. The mooring of this system is by nylon cable marked at intervals to indicate the height of the sensor.

Rain Gauge

The standard rain gauge consists of a metal funnel 8 inches in diameter, a measuring tube having 1/10 the cross-sectional area of the funnel, and a large container of 8 inches diameter. Normally precipitation is funneled into the measuring tube. The depth of water in the tube is measured using a dip stick having a special scale (because of the reduction in area). Measurements with this instrument, since they are made manually, give only accumulation since the last measurement.

The recording or weighing bucket rain gauge does give detailed time resolution of occurrence, and amount of precipitation, as a strip chart, with one revolution per day, is used. The gauge consists of a bucket, to hold the precipitation, on a scale, which weighs the precipitation and moves the pen arm, recording the total accumulation on the chart which is calibrated in inches.

Tipping bucket rain gauge has a bucket with two compartments beneath the collecting funnel. When one side of the bucket collects a given amount (usually 0.01 inch) of precipitation, the bucket tips and empties the precipitation, collecting the next portion in the other side. The bucket movements are recorded on a chart. The number of bucket movements and the time they occur indicate the rainfall amount and rate.

Humidity

Because of its influence upon certain chemical reactions in the atmosphere and its influence upon visibility and thus atmospheric transmittance, it is mandatory to measure the humidity.

The hygromograph measures both temperature and humidity, activating pen arms to give a continuous record of each element upon a strip chart. The chart generally can be used for seven days. The humidity

sensor generally used is human hair which lengthen as relative humidity increases and shorten with humidity decreases. Temperature measurements are usually made with a Bourdon tube, a curved metal tube containing an organic liquid. The system changes curvature with changes in temperature, activating the pen arm.

Humidity measurement by a psychrometer involves obtaining a dry bulb temperature and a wet bulb temperature from a matched set of thermometers. One thermometer bulb (wet bulb) is covered with a muslin wick moistened with distilled water. There must be enough air motion to cause cooling of the wet bulb due to evaporation of the water on the wick. A motor driven fan can be used to draw air at a steady rate past the moistened wick while a reading is taken. A sling psychrometer has both thermometers mounted on a frame which is whirled through the air to cause cooling by evaporation. Relative humidity is determined from the dry and wet bulb readings through the use of tables. Continuous measurements of humidity are not obtained using psychrometers.

APPENDIX IX

ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS REQUIREMENTS FOR EQUIPMENT

APPENDIX IX

Electromagnetic Interference Characteristics Requirements
for Equipment

(The following is an extract from pertinent U. S. Government specifications.)

(4.) GENERAL REQUIREMENTS

(4.1) Application of Standard. - The requirements of this standard shall be applied to electronic, electrical and electromechanical equipment as indicated hereinafter:

(4.1.1) Equipment. - The requirements of this standard shall be applied to units or equipments that are intended to operate as individual items. Individual equipment classes are defined in Table I. Application of each test requirement for the particular equipment class is shown in Table II.

(4.1.2) Government Furnished Equipment. - Equipment furnished by the Government to a contractor may, unless the test data is furnished by the Government, require testing by the contractor for conformance to the equipment item class and limit requirements. Application of suppression measures to meet the requirements shall be detailed in the control plan.

(4. 1. 3) Commercial Off-the-Shelf Equipment. -

(4. 1. 3. 1) When commercial off-the-shelf equipment is selected by the contractor all applicable tests required by this standard shall be performed and the test data submitted to the procuring activity to determine the EMI/EMC suitability in the end-item configuration. The EMI/EMC suitability shall be covered in the control plan (see 4. 2).

(4. 1. 3. 2) When C-E equipment certified to FAA Technical Standard Orders (Part 5. 1. 4 (a) and (b) are used with, or become part of any military equipment configuration, the requirements in 4. 1. 3. 1 apply.

(4. 1. 3. 3) Electrical and electromechanical equipment, not intended for use in tactical or critical military areas, are exempt for meeting the requirements of this standard unless specifically required by the procuring activity. When this equipment is procured for use in an unknown installation or for use in both tactical and nontactical installations the requirements stated in 4. 1. 3. 1 shall apply.

(4. 1. 4) Reprocurements of equipments designed to superseded documents. - Production type equipments (all classes) designed prior to the effective date of this standard and certified to superseded specifications or standards shall meet the appropriate requirements specified in Appendix A of this standard.

(4. 1. 5) Other EMI Requirements. -

(4. 1. 5. 1) If an equipment has met other emission and susceptibility requirements the test procedures and report may be submitted for evaluation by the procuring activity as evidence of meeting equivalent portions of this standard.

(4. 1. 5. 2) All equipments, other than Class I equipment, produced by a manufacturer, which are identical to those previously produced by the same manufacturer, tested in accordance with this standard and found satisfactory shall require minimal testing, as indicated in the approved test plan, to ascertain conformance with this standard. A copy of the previous test report shall be forwarded with the new test report for comparison and evaluation.

(4. 1. 6) Short-Duration Interference. - Short duration interference is not exempt from the requirements of this standard, unless specifically indicated in the individual equipment specification. The short-duration interference requirements given in Appendix A shall be used for repro-curements of equipments designed to superseded documents.

(4.1.7) Application of Standard for GSA Procurements. - The interpretation of and recommendations for compliance approvals to the requirements of this standard, as applied in GSA procurements, may be directed to the preparing activity of this standard.

(4.2) Interference Control Plan. - The interference control plan shall be a detailed plan outlining the interference control or reduction program, the engineering design procedures and proposed techniques that will be used to determine conformance with the requirements of this standard and that will enable the equipment to perform its operational function without interference from its parts and subassemblies. Approval of the control plan and compliance thereto does not relieve the contractor of the responsibility of meeting the applicable requirements of this standard. Technically justifiable deviations which are being, or are to be formally processed through contractual channels may be included in the control plan.

TABLE I - CLASSES OF EQUIPMENT

Class No.	Description
I	<p>Communication-Electronic (C-E) Equipment</p> <p>Any item, including subassemblies and parts, serving functionally in electromagnetically generating, transmitting, conveying, acquiring, receiving, storing, processing or utilizing information in the broadest sense. Sub classes are:</p>
IA	Receivers Using Antennas
IB	Transmitters Using Antennas
IC	<p>Non-Antenna C-E Equipment (such as counters, oscilloscopes, signal generators, rf and audio test equipment, computers, power supplies, digital equipment, electrically operated cameras and projectors, wire terminal image interpretation facilities, photographic processing equipment and other electronic devices working in conjunction with classes IA and IB).</p>
ID	<p>Electrical and electronic equipment and instruments which would affect mission success or safety if degraded or malfunctioned by internally generated interference or susceptibility to external fields and voltages such as autopilots, infrared devices, flight instruments, auto-compasses and electronic engine control devices).</p>
II	<p>Non-Communication Equipment,</p> <p>Specific subclasses are:</p>
IIA	<p>Non-Communication-Electronic Equipment - Equipment in which rf energy is intentionally generated for other than information or control purposes. Examples are ultrasonic equipment, medical diathermy equipment, induction heaters, rf stabilized arcwelders rf power supplies and uninterruptible power units (both rotary and solid state).</p>
IIB	<p>Electrical Equipment - Some examples are electric motors, hand tools, office and kitchen equipment, laundry and repair shop equipment, and lithographic processing equipment.</p>
IIC	<p>Accessories for Vehicles and Engines - Electrically and mechanically driven and engine electrical accessories such as gauges, fuel pumps, regulators, windshield wipers, turret motors, magnetos and generators, when tested off of the vehicle or engine. Applicable only to accessories for use on items of classes IIIA and IIIB.</p>
III	Vehicles, Engine-Driven Equipment

Table II - Test Requirements Applicable to Equipment Classes (Note 1)

	Equipment Class												Description of Test Method	Notes
	IA	IB	IC	ID	IIA (8)	IIB	IIC	IIIA	IIIB	IIIC	IIID (13)	IV (15)		
CE01	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	30 Hz to 20 kHz, Power Leads	(9)
CE02	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	0.03 to 20 kHz, Control and Signal Leads	(2, 6, 11)
CE03	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	0.02 to 50 MHz, Power Leads	
CE04	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	0.02 to 50 MHz, Control and Signal Leads	
CE05	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	30 Hz to 50 MHz, Inverse Filter Method	(4)
CE06	Y	Y	N	N	N	N	N	N	N	N	N	N	10 kHz to 12.4 GHz, Antenna Terminal	
CS01	Y	Y	Y	Y	N	N	N	N	N	N	N	N	0.03 to 50 kHz, Power Leads	
CS02	Y	Y	Y	Y	N	N	N	N	N	N	N	N	0.05 to 400 MHz, Power Leads	
CS03	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Intermodulation	
CS04	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Ref. of Undes, Sig. (2-Sig Gen Method)	(7)
CS05	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Cross-Modulation	
CS06	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Spike, Power Leads	
(T) CS07	Y	N	Y	N	N	N	N	N	N	N	N	N	Squelch Circuits	
CS08	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Ref. of Undes Sig. (1-Sig Gen Method)	(7)
RE01	Y	Y	Y	N	Y	N	N	N	N	N	N	N	0.03 to 30 kHz, Magnetic Field	(5)
RE02	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	14 kHz to 10 GHz, Electric Field	(12, 16)
RE03	N	Y	N	N	N	N	N	N	N	N	N	N	10 kHz to 40 GHz, Spurious and Harmonics, Radiated Technique	(3)
(T) RE04	Y	Y	Y	N	Y	N	N	N	N	N	N	N	0.02 to 50 kHz, Magnetic Field	(5)
RE05	N	N	N	N	N	N	N	Y	Y	Y	N	N	150 kHz to 1 GHz Vehicles and Engine Driven Equipment	(10, 14)
RE06	N	N	N	N	N	N	N	N	N	N	N	Y	Overhead Power Line Test	
RS01	Y	Y	Y	Y	N	N	N	N	N	N	N	N	0.03 to 30 kHz, Magnetic Field	(5)
RS02	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Magnetic Induction Field	
RS03	Y	Y	Y	Y	N	N	N	N	N	N	N	Y	14 kHz to 10 GHz, Elect. Field	(17)
(T) RS04	Y	Y	Y	Y	N	N	N	N	N	N	N	Y	14 kHz to 30 MHz	

Y = Test shall be performed as described in MIL-STD-462 or the approved test plan.

N = Test does not have to be performed, unless required by the test plan or procuring activity.

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Notes for Table II:

- (1) The test methods in MIL-STD-462 are designated by a series of numbers as shown hereinafter:
 - C = Conducted
 - R = Radiated
 - E = Emission
 - S = Susceptibility
 - " = Numerical order of test from 01 to 99.
 - T = New or Modified Test Procedure included for trial use, or as required by the procuring activity.
- (2) For Class IIIB items exceeding 600 volts AC or DC this test is not mandatory unless required by the procuring activity.
- (3) RE03 shall be performed when the operating frequency of the test sample is greater than 1.25 GHz, when the average power of the test sample is greater than 5 kW, or when the test sample's antenna is an integral part of the transmitter and cannot be replaced by a suitable dummy load.
- (4) Test method (CE05) may be submitted to the command or agency concerned for approval in the test plan, in lieu of CE01, CE02, CE03, or CE04 when the signal to be measured is generated by a single shot event or at repetition rates of less than 5 pps.
- (5) These tests (RE01), (T) RE04 and RS01) shall be performed on equipment operating at frequencies up to 30 MHz. Equipment operating at higher frequencies are exempt from testing.
- (6) For classes IIB, IIC, IIIA and IIIB perform the test over the frequency range of 150 kHz to 50 MHz. For class IIIB only, remove the 10 microfarad feed-through capacitor.
- (7) Perform either CS04 or CS08, as approved in the test plan.
- (8) Shall conform to F. C. C. Regulations, Part 15 or Part 18 as applicable. In addition, the applicable requirements of this standard shall be met for ultrasonic equipment, rf power supplies and uninterruptible power units (both rotary and solid state).
- (9) Class IIA shall be tested from 14 kHz to 20 kHz with this test procedure (CE01). However, when required by the individual equipment specification, the test shall be performed from 1 kHz to 20 kHz.

- (10) For class IIIC items, this test is not required above 400 MHz.
- (11) Electric hand tools (which fall under class IIB) shall be tested from 150 kHz to 30 MHz in accordance with the requirements and procedures of Method A-CE1 as specified in the Appendix to this standard.
- (12) Class IIB items, except electric hand tools, shall be tested from 150 kHz to 400 MHz. Electric hand tools shall be tested from 150 kHz to 30 MHz. Class IIC items shall be tested from 150 kHz to 1000 MHz.
- (13) Class IIID items shall comply with the requirements of SAE J551.
- (14) For class IIIB items exceeding 240 kVa, this test is not mandatory unless required by procuring activity or project manager.
- (15) These requirements are applicable for all MEP sets having outputs 240 kVa or less. When specified by the command or agency concerned MFP sets having power outputs greater than 240 kVa shall meet the requirements or RE02.
- (16) For Class V items, this requirement is applied between 14 kHz and 1000 MHz at a test distance of 1 meter. If test conditions preclude performing RE02 at a 1 meter distance, a distance of 6 meters may be used and the limit curve in Figure 26 corrected accordingly.
- (17) For Class V items with electronic circuitry for external regulation or control or sets with amplifiers for electronically controlling regulation, temperature, frequency, stability, and so forth, this requirement is applied between 2 MHz and 10 GHz in addition to CE03 and RE02.